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HUMAN PILOT RESPONSE DURING SINGLE- AND MULTI-AXIS TRACKING TASKS

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This report presents the results of a limited evaluation of human pilot response during single and multi-axis tracking tasks. A five member team from the USAF Test Pilot School conducted this evaluation at Buffalo, New York, from 8 to 11 October 1993. Five sorties totaling 7.6 hours were flown in the Calspan variable stability Lear II aircraft. Ground simulations in Lear II were also performed. Four different pitch and four different roll dynamics were evaluated using three different single and multi-axis tracking tasks. For each set of dynamics, primary pilot response parameters were recorded and examined using Fourier transform analysis in an attempt to provide a data base for pilot model development and validation. Pilot comments and Cooper-Harper ratings were also recorded. The flight test data gathered during this project are maintained at the Air Force Flight Dynamics Directorate (WL/FIGC), Wright-Patterson AFB, OH 45433 and are available for research purposes. This report serves as a guide for these flight test data and gives an initial look at the test results.

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PREFACE

This report presents the results of a limited evaluation of human pilot response during single and multi-axis tracking tasks. This evaluation was requested by the Air Force Flight Dynamics Directorate, Wright-Patterson AFB, Ohio, and was conducted by a five person test team from the USAF Test Pilot School (TPS) Class 93A as part of the Test Management Phase syllabus. Testing was conducted at Calspan Corporation, Buffalo, New York, between 7 and 12 October 1993. Five sorties totaling 7.6 hours were flown in the Calspan variable stability Lear II aircraft. Ground simulations in Lear II were also performed. The test was conducted under Job Order Number 996TPU00 as directed by the Commandant, USAF TPS.

The test team would like the thank Mr. Tom Twisdale, 412 Test Wing Engineering Division, and Mr. Ralph Smith, High Plains Engineering, for their technical assistance with this challenging project. The test team also would like to thank Mr. Mike Nelson, USAF TPS Curriculum Advisor, and Lt. Brian Krauss, 412 Test Wing Technical Support Division, for their assistance with software validation and simulation, respectively. Finally, the test team would like to thank Mr. Dave Leggett, Air Force Flight Dynamics Directorate, whose vision and support made this project possible.

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EXECUTIVE SUMMARY

This report presents the results of a limited evaluation of human pilot response during single and multi-axis tracking tasks. Testing was conducted at Calspan Corporation, Buffalo, New York, between 8 and 11 October 1993. Five sorties totaling 7.6 hours were flown in the Calspan variable stability Lear II aircraft. Ground simulations in Lear II were also performed. This evaluation was requested by the Air Force Flight Dynamics Directorate (WL/FIGC), Wright-Patterson AFB, Ohio.

Four different pitch and four different roll dynamics were evaluated using three different single and multi-axis tracking tasks. For each set of dynamics, primary pilot response parameters were recorded and examined using Fourier transform analysis in an attempt to provide a data base for pilot model development and validation. Pilot comments and Cooper-Harper ratings were also recorded.

All objectives but one were met. The frequency response analysis approach used in this project for the evaluation of pilot compensation on normal acceleration cues was not effective. It produced the frequency response of the aircraft and not the pilot, making an examination of pilot compensation on this parameter impossible.

The flight test data gathered during this project will be maintained by the Air Force Flight Dynamics Directorate and made available for research purposes to requesting agencies. This report serves as a guide for this flight test data and gives an initial look at the test results.

The pilot delay between task command and stick force was estimated at 0.27 seconds. This is consistent with the generally accepted value of 0.25 seconds. Stick position, however, lagged stick force by an additional 0.1 seconds due to the stick dynamics lag effects.

A frequency response analysis of stick deflection to task error revealed that the predicted *pilot* magnitude was consistent with conventional pilot modeling theory for the pitch and roll axes cases. The phase, however, was not consistent with conventional pilot modeling predictions due to the large amount of phase lead present at higher frequencies. This phase lead was especially noticeable for cases with added delay. For all cases evaluated the pilot response appeared to be strongly related to the aircraft dynamics. There were no noticeable differences between airborne and ground simulation responses.

Finally, the pitch axis pilot models in MIL-STD-1797A did not successfully predict Cooper-Harper ratings or handling qualities levels for the dynamics evaluated during this project. Additionally, the product rules commonly used to predict multi-axis Cooper-Harper ratings from single axis Cooper-Harper ratings were deemed unacceptable because they excessively amplified ratings variations.

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INTRODUCTION

GENERAL

This report presents the results of a limited evaluation of human pilot response during single and multi-axis tracking tasks. A five-member team from the USAF Test Pilot School (TPS) conducted this evaluation at Buffalo, New York, from 7 to 12 October 1993. Five sorties totaling 7.6 hours were flown in the Calspan Lear II, a variable stability version of the Learjet 25. In addition, a 1.4 hour calibration flight was flown by Calspan personnel. A 12 hour ground simulation in Lear II was also conducted. Four different pitch and four different roll axis dynamics along with the 16 multi-axis combinations were evaluated (24 cases total) using three different tracking tasks. For each case, primary pilot response parameters were recorded and analyzed using Fourier transform techniques. Pilot comments and Cooper-Harper ratings (Reference 1) were also recorded. The Commandant, USAF TPS, directed this project in accordance with the Test Management Phase curriculum under Job Order Number P996TPU00.

BACKGROUND

Handling qualities prediction requires some degree of pilot-in-the-loop analysis. Pilot models are essential to this analysis. Currently, pilot model development faces two obstacles, a lack of insight into human pilot response and a basis for validation. This test project attempts to address each of these deficiencies.

There have been few attempts to describe pilot behavior during airborne tracking tasks using frequency response analysis. A majority of the research has been limited to examining the relationship between aircraft dynamic characteristics, such as damping or frequency, and pilot opinion ratings.

One of the earliest attempts to measure human pilot behavior was made by Edward Seckel and Duane McRuer in a 1958 Princeton University study, *Human Pilot Dynamic Response in Flight and Simulator* (Reference 2). A Navion aircraft was used in the flight portions of the experiment, and the same airplane was simulated on the ground using analog computer techniques. Seckel used frequency response analysis to estimate the quasi-linear describing functions of several pilots when engaged in lateral and longitudinal tracking tasks with random appearing forcing functions. He concluded that pilot behavior could be crudely modeled by a gain, lead, lag, and delay.

In 1965 McRuer and Krendel conducted a controlled measurement of human pilot behavior using frequency response methods. Their effort is summarized in *Human Pilot Dynamics in Compensatory Systems* (Reference 3). Using a pitch axis tracking task generated on a laboratory oscilloscope, they found that for very simple dynamics the quasi-linear pilot can be represented by the following transfer function.

$$Y_p = K_p \cdot e^{-j\omega\tau} \cdot \frac{(T_L \cdot j\omega + 1)}{(T_I \cdot j\omega + 1)} \cdot \frac{[T_K \cdot j\omega + 1]}{[T_K' \cdot j\omega + 1]} \cdot \frac{1}{(T_N \cdot j\omega + 1) \cdot \left[\left(\frac{j\omega}{\omega_n}\right)^2 + \frac{2\zeta_n}{\omega_n} + 1\right]}$$

GAIN	PURE DELAY	SERIES EQUALIZATION	VERY LOW FREQUENCY LAG-LEAD	NEUROMUSCULAR SYSTEM

Where

$j\omega$	Laplace Variable for Random Input
Y_p	Pilot Output
K_p	Pilot Gain
τ	Pilot Delay
T_L	Pilot Lead Time Constant
T_I	Pilot Lag Time Constant
T_K	Very Low Frequency Pilot Lead Time Constant
T'_K	Very Low Frequency Pilot Lag Time Constant
T_N	Neuro-muscular Time Constant
ω_n	High Frequency Neuro-Muscular Natural Frequency
ζ_n	High Frequency Neuro-Muscular Damping Ratio

Limiting the frequency range of interest to 0.1 to 10 radians per second, the very low frequency lag-lead and the high frequency complex poles of the neuromuscular system can be ignored leaving the classical pilot model[1].

$$Y_p = K_p \cdot \frac{(T_L \cdot j\omega + 1)}{(T_I \cdot j\omega + 1)\,(T_N \cdot j\omega + 1)} e^{-j\omega\tau}$$

The T_N term represents a neuromuscular lag at about 8 radians per second. As shown, the classical pilot model also includes a pure delay as well as a gain, lead, and lag.

MIL-STD-1797A (Reference 4) includes several pilot models for evaluating pitch and roll dynamics. Only one of these models, the Neal-Smith model, adopts the classical pilot model approach. A second, the bandwidth criterion, estimates an aircraft's handling qualities based on the shape of the aircraft's Bode plot. The rest of the models examine the aircraft's time response to open loop inputs and make no attempt to model human pilot behavior.

[1] $j\omega$ was used instead of the classical Laplace variable s because these equations only hold for random appearing inputs.

A 1990 study conducted by Systems Technology, Inc. (STI), *Piloted Simulation Evaluation of Multiple Axis Flying Qualities* (Reference 5) attempted to describe pilot response during multi-axis compensatory tracking tasks. STI evaluated several different aircraft dynamics using the Large Amplitude Multi-Mode Aerospace Research Simulator (LAMARS) at Wright-Patterson Air Force Base, Ohio. They expanded the minimum flying qualities data base and drew relationships between single and multi-axis ratings. They also made some important conclusions concerning pilot behavior during multi-axis tasks. This STI study did not apply frequency response analysis to human pilot behavior.

RESEARCH VEHICLE DESCRIPTION

The pilot was the true test item for this test program. The three test pilots used for this evaluation had a variety of operational backgrounds. Their flight experience is described in detail in Appendix A.

The Calspan Variable-Stability Lear II was used as the research vehicle for this evaluation. It was a production Learjet 25 aircraft that was extensively modified for use as an in-flight simulator. The basic aircraft, shown in Figure B2, was a low-wing, t-tail, twin engine jet.

The safety pilot's (left seat) control column was connected directly to the aircraft's control surfaces through the production reversible push rod system and mirrored the surface positions. The evaluation pilot's (right seat) controls were removed and replaced with a variable electro-hydraulic feel system that was part of the in-flight simulation system. A digital computer system was located in the main cabin. It was designed to model aircraft and artificial feel systems and record in-flight data. A color flat panel display, located on the main instrument panel in front of the evaluation pilot's station, displayed the single and multi-axis tracking tasks. A detailed description of the Lear II and the flat panel display is given in Appendix B.

The aircraft limits are shown in Appendix B, Table B1. Safety trips in Lear II prevented the evaluation pilot from exceeding the aircraft limits during simulation. If a limit was approached, the safety system would end the simulation and give control of the aircraft to the safety pilot. A complete list of safety trip parameters is given in Table B2.

The parameters shown in Table 1 were recorded for each test case with a sampling rate of 100 hertz (Hz). Data were stored directly on to 90 Megabyte personal computer (PC) compatible Bernoulli drive cartridges. Sensor accuracies and resolutions are presented in Table B3.

All task and pilot comments were recorded by a miniature color camera system. This camera recorded the tracking task display and pilot comments from a direct feed on 8 mm, two-hour video cassettes.

Table 1: Data Parameters

Parameter Category	Parameter Name	Symbol	Parameter Category	Parameter Name	Symbol
Aerodynamic Parameters	Angle-of-Attack	α	Control Parameters	Elevator Deflection	δ_e
	Sideslip Angle	β		Rudder Deflection	δ_r
	Pitch Angle	θ		Aileron Deflection	δ_a
	Roll Angle	ϕ		Longitudinal Stick Deflection	δ_{es}
	Pitch Rate	q		Rudder Pedal Deflection	δ_{rp}
	Roll Rate	p		Lateral Stick Deflection	δ_{as}
	Yaw Rate	r		Longitudinal Stick Force	F_{es}
Other	Time	t		Rudder Pedal Force	F_{rp}
	Normal Acceleration - x	n_x		Lateral Stick Force	F_{as}
	Normal Acceleration - y	n_y	Display Parameters	Pitch Command	θ_c
	Normal Acceleration - z	n_z		Roll Command	ϕ_c

OBJECTIVES

This test had three major, interrelated objectives. The first was to record and examine human pilot response during airborne tracking tasks. The second major objective was to record and examine pilot comments and Cooper-Harper ratings during airborne tracking tasks. The final major objective was to record ground simulation data for comparison with airborne results. The specific objectives were:

1. Record and examine pilot response parameters during airborne single and multi-axis tracking tasks that can be used as a data base for pilot model development and validation.

   A. Using the sum-of-sines, discrete, and regulator tracking tasks described in Appendix C, record the parameters shown in Table 1 for each of the pitch and roll cases described in Appendix D.

   B. Using the data obtained during the sum-of-sines tracking task described in Appendix C, perform a frequency response analysis of stick force and displacement to task error for each of the pitch and roll cases described in Appendix D. Evaluate the feedback loops used by the pilot and the compensation used in each loop. Compare the results with the predictions of the classical pilot models given in MIL-STD-1797A (Reference 4) and the optimal pilot model developed by Systems Technology, Incorporated (Reference 9).

C. Using data obtained during the sum-of-sines and disturbance rejection tasks described in Appendix C, perform a frequency response analysis of stick force and displacement to normal acceleration at the pilot's station (n_{zp} and n_{yp}) for each of the pitch and roll cases described in Appendix D. Evaluate the compensation used by the pilot in each loop. Compare the results found during the sum-of-sines tracking task with those found during the disturbance rejection task.

2. Investigate the relationship between single and multi-axis Cooper-Harper ratings.

A. Using the airborne tracking tasks described in Appendix C, gather Cooper-Harper ratings and pilot comments for each of the pitch and roll cases described in Appendix D.

B. Compare the Cooper-Harper ratings and pilot comments for the multi-axis cases with product rule predictions (Reference 5) made from the single axis ratings.

3. Compare pilot response during ground simulation with airborne pilot response for single and multi-axis tracking tasks.

A. For the sum-of-sines and discrete tracking tasks described in Appendix C, record the parameters shown in Table 1 for each of the pitch and roll cases described in Appendix D.

B. Using data obtained during the sum-of-sines task described in Appendix C, perform a frequency response analysis of stick force and displacement to tracking error for each of the pitch and roll cases described in Appendix D. Evaluate the feedback loops used by the pilot and the compensation used in each loop. Compare the results with the predictions of the classical pilot model given in MIL-STD-1797A (Reference 4), the optimal pilot model developed by System Technology, Inc (Reference 9), and airborne results.

C. Using the tracking tasks described in Appendix C, gather Cooper-Harper ratings and pilot comments for each of the pitch and roll cases described in Appendix D during ground simulation. Compare the ground and airborne Cooper-Harper ratings.

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TEST AND EVALUATION

GENERAL

This test used three different tracking tasks to evaluate four pitch and four roll axis dynamics cases both individually and in multi-axis combinations (24 cases total). Fourier analysis was then used to evaluate several pilot response parameters in an attempt to provide insight into human pilot behavior. This project was divided into two phases. During the first phase the dynamics, tracking tasks, and data reduction software were verified. The second phase consisted of ground simulation and airborne data collection using Lear II.

TEST PROCEDURES

Ground Simulation at Edwards AFB

Prior to testing at Calspan, the project engineers and project pilots flew the single and multi-axis dynamics cases described in Appendix D using the ground simulator provided by 412 TW/TSWS at Edwards AFB. The purpose of this simulation was to rehearse test procedures and crew coordination, verify the suitability of the aircraft dynamics and tracking tasks, and provide data for software verification. Data from these simulations were processed using the Air Force Flight Test Center (AFFTC) frequency response analysis computer program that runs on a CYBER mainframe computer. This program was validated by previous AFFTC tests. As explained in Appendix E, the MatLab frequency response analysis software used for data reduction in this project yielded virtually identical results.

During this ground simulation, flight cards and test procedures were also evaluated for correctness and repeatability. The pilots reviewed guidance for the appropriate use of the Cooper-Harper and pilot induced oscillation (PIO) scales presented in Appendix F. They also practiced assigning ratings during the ground based simulations prior to actual data collection. This rehearsal emphasized the need to provide three Cooper-Harper ratings, one for each tracking task, rather than a single rating for each dynamics case using all three tasks.

Checkout Flight at Calspan

Calspan performed a dedicated checkout flight prior to the first flight and ground simulation tests in the Lear II. During this flight, Calspan validated the tracking tasks and aircraft dynamics used for this test. They also set the control system gains so that longitudinal Case 1 and lateral Case A would have Level 1 handling qualities during tracking.

Ground and Airborne Simulation in Lear II

Ground and airborne simulations were flown in the Lear II at Calspan in Buffalo, New York. For the ground evaluations, the Lear II was operated in the ground simulation mode inside the Calspan hanger. The Lear II had the unique ability to ground simulate the requested dynamics with the same delays as the airborne simulations. The ground simulations provided pilot modeling data for comparison with that collected during airborne simulations, and served as a dress rehearsal for the airborne evaluations. In-flight testing was conducted under day, visual meteorological conditions (VMC) with no more than occasional light turbulence.

The project pilots evaluated the single and multi-axis test cases described in Appendix D. During ground simulations each single axis case was flow twice, and each multi-axis case was flown once. For the airborne simulations, all single axis cases were evaluated three times, and all but two multi-axis cases were evaluated twice. In planning the specific test points, project engineers ensured adequate pilot variability checks by assigning some pilots the same cases twice and by assigning some cases to more than one pilot. The dynamics cases were also evaluated in a random order.

For each test case, the pilot flew the discrete tracking task, followed by the sum-of-sines tracking task and the regulator task. The regulator tasks were only flown during airborne simulations since these tasks were designed to evaluate normal acceleration feedback cues. These tasks are described in Appendix C. Each tracking task was performed as follows:

(1) Data on
(2) Begin the task
(3) Begin scoring five seconds after task starts
(4) Score for 40.96 seconds
(5) End the task
(6) Data off
(7) Debrief task

The Fourier analysis software used in this test required 2^n samples. A task duration greater than 30 seconds was required to allow the pilot ample time to evaluate the aircraft. Thus, a task duration of at least 40.96 seconds, using a sampling rate of 100 hertz and providing 4096 or 2^{12} data points, was necessary. A 53 second task duration was used for this project to provide ample time to start and finish the task.

Immediately after each task, the pilot assigned a pilot induced oscillation (PIO) rating as well as a Cooper-Harper rating using the PIO and Cooper-Harper rating scales in Appendix F. The desired and adequate criteria used for the Cooper-Harper ratings are given in Appendix C. The pilot and flight test engineer then completed the test point comment card shown in Appendix F. Finally, the project engineer provided the project pilot with the percentage of time the desired and adequate criteria were met as computed by the Lear II simulation computer, and the project pilot was asked for a second Cooper-Harper rating. This second rating was not used in data analysis.

The parameters in Table 1 were recorded with a sampling rate of 100 hertz for each test case. The percentage of time the desired and adequate criteria were met as computed by the Lear II simulation computer were saved in separate scoring files. Qualitative pilot comments as well as Cooper-Harper and PIO ratings were recorded by the project engineer. Pilot comments along with each task display were recorded on 8 millimeter video cassettes.

Data Reduction and Analysis

In an effort to gain insight into human pilot response, the relationship between tracking task error, normal acceleration, and pilot response was examined. From a model identification standpoint this can be drawn as in Figure 1, where task error or normal acceleration is the input to the pilot and stick force and displacement are the pilot's output.

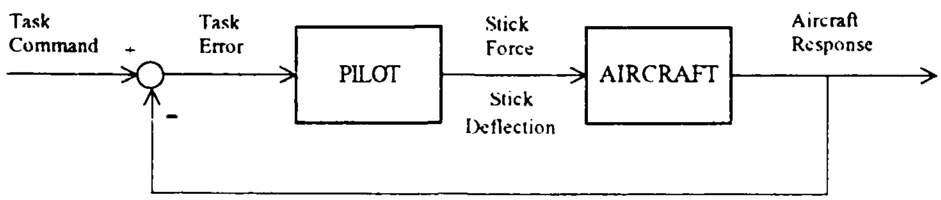

Figure 1: Pilot Response Block Diagram

If a random appearing task with the proper frequency content is used, the pilot exhibits sufficiently linear behavior to allow a frequency response analysis of this input-output frequency response relationship (Reference 3). The frequency response analysis for this project was accomplished using the MatLab fast Fourier transform software described in Appendix E. Once validated, this software was used to compute the fast Fourier transform of the time sampled data for those transfer functions specified in the objectives section of this report.

TEST RESULTS

General

All objectives were not met. The frequency response analysis approach used in this project for the evaluation of pilot compensation on normal acceleration cues was not effective. This prevented the pilot compensation evaluation required by objective 1C. All other objectives were met. Pilot and aircraft response parameters were recorded during ground and airborne evaluations of the dynamics described in Appendix D using three different tracking tasks. Cooper-Harper ratings and pilot comments were also recorded and transcribed into this report. The remainder of this section presents a preliminary analysis of this data.

Data Base

Description

The dynamics described in Appendix D were evaluated using the three tracking tasks described in Appendix C. All single axis dynamics cases were evaluated twice during ground simulation and three times during airborne simulation. All multi-axis dynamics cases were evaluated once during ground simulation. All but two of the multi-axis cases were evaluated twice during airborne simulation. During the evaluations the parameters listed in Table 1 were recorded in MatLab format using a sampling rate of 100 samples per second (objective 1A and 3A). Cooper-Harper ratings and pilot comments were also recorded. (objective 2A). The flight test data from each run is included in the data base described in Appendix G. Several scoring variables, such as percentage of time the desired and adequate criteria were met, were also recorded and were included in the data base. Finally, all of the software used for analysis in this report was included in the data base for repeatability of results.

Qualitative Comments

Several factors concerning the setup of this experiment should be noted when conducting further analysis of this flight test data. None of these factors had any noticeable effect on data quality, but they are presented here for consideration.

Two deficiencies in the experimental setup were noted by the project pilots. The project pilots felt, however, that these deficiencies did not significantly affect data quality. First, the brightness of the display was the minimum acceptable for the task. Often the aircraft had to be maneuvered prior to beginning a task to prevent the sun from shining directly onto the display. Glare and display brightness were not factors for the ground simulations. Second, the task command bar shape was slightly confusing when it overlapped the fixed pipper attitude reference. When step pitch commands were made from the overlap position, the pilots sometimes confused the fixed pipper reference for the command bar and initially reacted in the wrong direction. This occurred only rarely and the pilots felt it should not affect overall data quality.

Several issues that concerned the test team prior to the evaluation were resolved satisfactorily. First, the pilots felt that the task length of approximately 53 seconds was the minimum required for an adequate evaluation. Second, pilot fatigue was never a problem on the flights. Two evaluation pilots were carried on each flight and each pilot flew 40 minute evaluation sessions. Third, despite flying nearly one hundred tracking tasks, task memorization never occurred. While the pilots became familiar with the general flow of the tasks, they never learned to anticipate a specific command. Fourth, disorientation was never a factor during the airborne tracking tasks. This was largely due to the outside peripheral attitude cues available during the tasks. The horizon line (see Figure B3) was critical in preventing disorientation during ground simulation, but was not referenced by the project pilot in flight. Finally, blind evaluations were essential for assigning Cooper-Harper ratings without bias.

Validation

The simulated dynamics used for this evaluation were verified using analog matching techniques. To accomplish the analog matching, actual stick deflection and stick force data were used to find the expected aircraft response using linear simulation commands in MatLab. This predicted response was then compared with the actual aircraft response. The predicted response was shifted up or down by the initial flight condition. The initial trim condition was also accounted for by shifting the stick deflection and force data before the MatLab simulation. For example, the analog match of roll angle (ϕ) to stick force for Case A, as shown in Figure D3, was made in the following manner. First, the stick force flight test data were shifted upward to account for the initial trim condition by adding 0.65 pounds to each element in the vector. Second, this stick force data were used as the input to the linear simulation of the desired dynamics using the command *lsim* in MatLab. The output of this MatLab simulation was then adjusted for the initial roll condition by subtracting one degree from each element. Finally, the actual and predicted roll angle were plotted as a function of time as shown in Figure D3. Frequency response analysis was performed with and without including the initial trim and flight conditions. As expected these adjustments had no effect on the frequency response data.

Similar techniques were used to perform analog matches of the remaining dynamics cases used for this evaluation. The resulting plots are shown in Figures D4 through D6. In all cases the matches were satisfactory. In some cases the simulated and actual dynamics began to diverge after about 30 seconds due to errors and non-linearities in the Lear II modeling system, but this divergence was not significant. Also, this analog matching revealed that the effective stick force gradient in the roll axis was slightly lighter than requested (4.4 pounds per inch). This also was not considered significant for the purposes of this project because the desired range of handling qualities was achieved.

Finally, all recorded data parameters were checked for accuracy to the maximum extent possible. This was done using analog matching and linear simulation on MatLab. Also, the time histories of all variables were reviewed and checked for reasonableness.

Summary

The experimental setup was valid and the simulated dynamics and recorded data parameters were validated by analog matching techniques. The data base described in

Appendix G includes valuable flight test data and warrants further examination. **Use the flight test data gathered during this project for further analysis (R1)**[2].

Cooper-Harper Ratings

General

Pilot comments and Cooper-Harper ratings were recorded and are presented in Appendix H (objectives 2A and 3C). The dynamics evaluated for this project produced a wide range of pilot response as evidenced by the spread in Cooper-Harper ratings. These ratings ranged from 1 to 8. Table H1 and H2 summarizes theses ratings by dynamics case for ground and airborne evaluations, respectively. This table also includes the pilot induced oscillation (PIO) rating and the percentage of time the pilot met desired and adequate criteria during each task. Table H3 contains the pilot comments for all of the ground evaluations. These comments are presented by record number for cross-reference with the video tape included in the data base (see Appendix G). Finally, Table H4 contains the pilot comments for all airborne evaluations.

Tracking Tasks

The three tasks used to conduct the evaluations for this project accentuated different types of handling qualities. The Cooper-Harper ratings assigned during each task are displayed graphically in Figures I1 through I3. The evaluation pilots felt that the discrete task was the best task for evaluating handling qualities during gross acquisition, while the sum-of-sines task was the best task for evaluating handling qualities during fine tracking. Further, the evaluation pilots felt that the discrete tracking task could be flown more open loop. As shown in these figures, the ratings assigned using either of these tasks were similar. The Cooper-Harper ratings assigned using the discrete task had the lowest variability (± 1 rating), however, and were used for the analysis in this report.

The regulator task was not an acceptable task to use for assigning Cooper-Harper ratings. It was designed for the frequency response analysis of normal acceleration feedback cues. Thus, the magnitude of the task was not high enough to allow the pilot to adequately evaluate the handling qualities of the dynamics cases. As shown in Figures I1 through I3, the Cooper-Harper ratings assigned during the regulator task varied excessively. The Cooper-Harper ratings of Case D, for example, ranged from 4 to 8. **Do not use the Cooper-Harper ratings assigned during the regulator task for standard pilot opinion rating analysis (R2).**

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[2] Numerals preceded by an *R* within parentheses at the end of a paragraph correspond to the recommendation numbers tabulated in the Conclusions and Recommendations section of this report.

Single Versus Multi-Axis Ratings

The Cooper-Harper ratings displayed in Figures I4 and I5 are arranged so that the multi-axis ratings can be compared with the ratings for the single axis components (Objective 2). In all but three cases the single axis tasks received better ratings than the multi-axis combination, but there were no definite trends to suggest a statistical relationship.

Several product rules for estimating multi-axis ratings from single axis ratings are described in Reference 4 and listed on page 116. These formulas are based on different types of statistical fits to past data. Figures I6 to I9 display the actual multi-axis ratings and product rule predictions (objective 2B). The actual Cooper-Harper ratings never differed by more than 2. This variance is squared, however, when using the product rules resulting in a predicted Cooper-Harper rating range of as much as 4 ratings. The predicted rating for Case 1B, for example, was between 1 and 5. This wide variance made the product rules useless. The product rules attempt to apply a mathematical operation to the Cooper-Harper rating process and cannot account for the variances that result. **Do not use the product rules in Reference 4 and Appendix I to estimate multi-axis Cooper-Harper ratings from single axis Cooper-Harper ratings (R3).**

Airborne Versus Ground Ratings

Ground and airborne Cooper-Harper ratings are compared in Figures I10 through I12 (objective 3C). As shown in these figures, half of the dynamics cases received better ratings on the ground and half received better ratings in the air. The evaluation pilots felt that disorientation was not a factor in flight, but bad dynamics seemed worse in the air due to the uncomfortable motions they produced. However, workload was higher during the ground evaluations due to a lack of visual and vestibular cues. The ground simulations for this project were good predictors of airborne results.

Pilot Delay

Pilot delay was estimated using the discrete tracking task described in Appendix C. As shown in Figure J1, the discrete task consisted of a series of steps and ramps separated by as much as 5 seconds. Pilot delay was estimated by measuring the time between the command change and the stick force or deflection. The initial step in the task was not appropriate for this measurement because the pilots were not actively involved in the task until approximately 5 seconds after it started. Also, to minimize the effects of previous task commands following a period without any commands was chosen. The pilot delay values presented in Table J1 were found using the step command which occurred about 45 seconds into the task. This step command was separated from previous commands by five seconds. Figure J1 displays the commanded step input and the longitudinal stick force response. This area of interest is enlarged in Figure J2. As shown in Figure J2, the step command occurred at 44.88 seconds and the longitudinal stick force began to increase rapidly at approximately 45.15 seconds, giving a delay of 0.27 seconds. As shown in Table J1, pilot delay (between task command and stick force) ranged from 0.24 to 0.31 seconds. The mean was 0.27 seconds and the standard deviation was 0.016 seconds. The pilot delay times did not vary significantly by pilot or by dynamics case. This estimation was consistent with the conventionally accepted value of 0.25 seconds. It is important to note that in all cases, stick deflection lagged stick force by 0.1 ($\pm$0.01) seconds reflecting the lag inherent in the stick dynamics. **When analyzing stick deflection command systems increase the pilot delay values used in pilot models to account for the stick dynamics lag effects (R4).**

Frequency Response Analysis

General

From a linear systems perspective, the primary inputs to the pilot were assumed to be normal acceleration and task error. The pilot's primary outputs were assumed to be stick force and deflection. A frequency response analysis of stick forces and deflections to task error was performed for all ground and airborne sum-of-sines tracking tasks. Additionally, a frequency response analysis of stick forces and deflections to normal acceleration was performed for all airborne sum-of-sines and regulator tracking tasks. This analysis was conducted in an attempt to provide insight into human pilot behavior by identifying the relationship between the pilot input and output variables. The preliminary results of this analysis are presented in the following sections.

Stick Force Versus Stick Deflection

The dynamics described in Appendix D were implemented as a position command system for this project. Stick force and displacement were related by a high frequency stick dynamics term and a force gradient. As shown on page D5, the force gradients used for this project were 6 pounds per inch for pitch and 4.4 pounds per inch for roll. The stick dynamics were implemented as a second order complex pole pair with a corner frequency of 16 radians per second. The Bode plot of longitudinal stick deflection to force is shown in Figure 2.

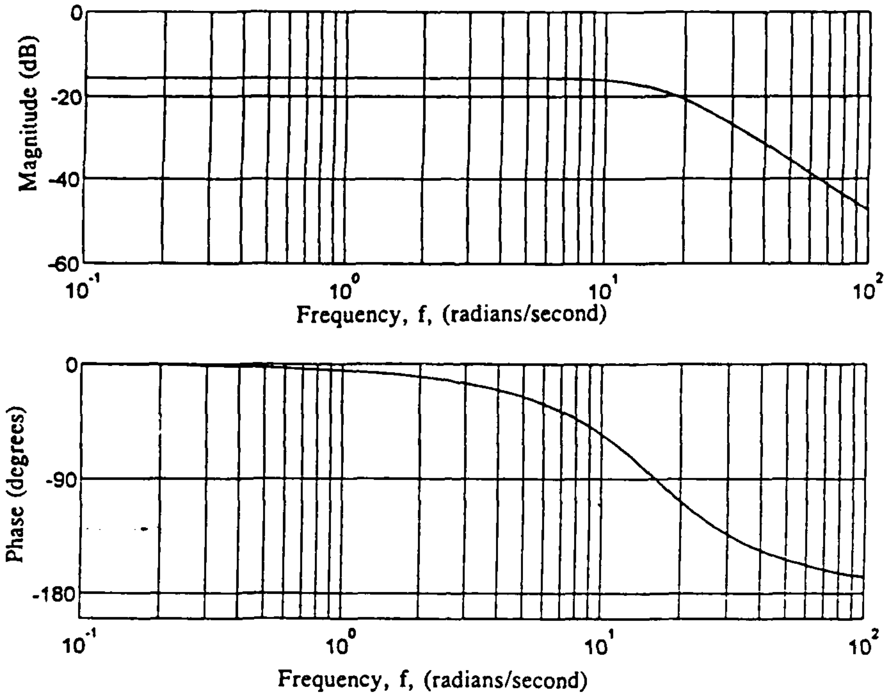

Figure 2: Bode Plot of Longitudinal Stick Displacement to Force

A sample stick force frequency response plot is shown in Figure K1. The stick deflection frequency response plot for the same run is shown in Figure K2. If the stick force response in Figure K1 is summed with the stick dynamics shown in Figure 2 above, the result will be virtually identical to the stick deflection response in Figure K2. This was the case for all data runs made for this project. The only difference between the stick force and deflection frequency response plots was the frequency response of the stick dynamics. Because of this, the remaining analysis in this report focused only on stick deflection.

Single Axis Stick Deflection to Task Error

A frequency response analysis of stick deflection to tracking task error for all single axis sum-of-sines tracking tasks was completed (objective 1B). A representative cross-section of this data is presented in Appendix K. The analysis for this project focussed on the power spectral density of the pilot input and output, measurement error analysis, and pilot compensation.

The power spectral density of a typical single axis pitch axis case is shown in Figure K3. This figure shows that the power of the pilot output (stick deflection) was roughly equivalent to the power of the pilot input (task error) until about seven radians per second. This was the case for all single axis cases, implying that the pilots were aggressive when tracking the command bar.

A measurement error analysis of several cases was conducted by taking the cross spectral densities of several parameters and confirming their consistency. This was accomplished by comparing the frequency response of stick deflection to error with the difference between the frequency response of stick deflection to pitch command and error to pitch command. This is illustrated by the following equation.

$$\frac{\delta_{es}}{e} = \frac{\dfrac{\delta_{es}}{\theta_c}}{\dfrac{e}{\theta_c}}$$

Since the above transfer functions are in the frequency domain, dividing them is equivalent to subtracting the gain and phase of one from the other.

$$\textit{Gain:} \quad \left|\frac{\delta_{es}}{e}\right| = \left|\frac{\delta_{es}}{\theta_c}\right| - \left|\frac{e}{e_c}\right|$$

$$\textit{Phase:} \quad \angle\left(\frac{\delta_{es}}{e}\right) = \angle\left(\frac{\delta_{es}}{\theta_c}\right) - \angle\left(\frac{e}{e_c}\right)$$

Thus, the two methods of determining the frequency response of stick deflection to error should produce identical results.

The frequency response of stick deflection to task error for pitch axis Case 1 (damped without delay) is shown in Figure K4. The frequency responses of stick deflection and task error to pitch command for the same run are shown in Figures K5 and K6. Using the method described above, the magnitude and phase values shown in Figure K6 were subtracted from those in Figure K5 and then compared with the directly computed values in Figure K4. The plots in Figure K7 show the difference between the magnitudes and phases computed using the two methods as a function of frequency. Despite an extremely low coherence in some of the data, the two methods produced virtually the same result out to 10 radians per second.

Pilot compensation was examined using the stick displacement to task error frequency response plots for all of the single axis dynamics cases. Four representative frequency response plots are shown in Figures K8 through K11. Figure K8 is for dynamics Case 1 (well damped without delay). Figure K9 is for Case 4 (lightly damped with 0.2 second delay). Figure K10 is for dynamics Case A (quick roll mode without delay). The final plot, Figure K11 is for Case D (slow roll mode time constant with delay). As shown in these figures, the magnitudes were consistent with the conventional pilot modeling theory described previously in this report and in Reference 2. According to this theory, the pilot acts as a gain, lead, lag, and delay near the cross-over frequency when controlling simple pitch axis dynamics[3]. The phase, however, was not consistent with this form of pilot compensation due to the large amount of phase lead present at higher frequencies. As shown in Figure K9, this phase lead is especially noticeable for cases with delay. More importantly, the pilot response appears to be strongly related to the aircraft dynamics.

To see this relationship, frequency responses of the combined pilot-vehicle systems of the same four runs are presented in Figures K12 through K15. These plots were formed by adding the frequency response of the pilot (stick deflection to task error) with that of the aircraft (pitch or roll angle to stick deflection). As shown in Figures K12 and K13, the combined pilot-aircraft system is consistent with theory for the pitch axis in that the frequency response resembles an integrator near the cross-over frequency. Note also that the cross-over frequency of the combined system dropped from 1.9 radians per second for the best case (Figure K12) to 1.6 radians per second for the worst case (Figure K13). To achieve this response near the crossover frequency, the pilot behavior emulated higher order dynamics and added more phase lead than possible with a conventional pilot model lead-lag system.

A similar result was observed in the roll axis. As shown in Figures K14 and K15, the frequency response of the combined aircraft-pilot system resembled an integrator near the crossover frequency. This crossover frequency dropped from 1.6 radians per second for the best case (Figure K14) to 1 radian per second for the worst case (Figure K15). Again, to achieve this response, the pilot added more phase lead than possible with the conventional pilot lead-lag model. **Extend the form of the conventional pilot crossover model to account for pilot response when controlling short period or higher order pitch axis dynamics (R5).**

As expected, there were slight differences between pilots when flying the same case. In Figures K16 and K17, the crossover frequency of the combined pilot-aircraft system was lower when pilot *S* flew Case 1 (Figure K17) than when pilot *G* flew Case 1 (Figure K16). Pilots were consistent, however, when they flew the same case twice. As shown when comparing Figures K18 and K16, pilot *G* had virtually the same response and system crossover frequency both times he flew Case 1.

Normal Acceleration

The frequency response of stick deflection to normal acceleration for Case 1 using the sum-of sines is shown in Figure L1 (objective 1C). Similar plots for the same case using the regulator task are shown in Figure L2. Unfortunately, because the tracking tasks used for this project did not directly command an acceleration, these frequency responses represented the inverse of the aircraft dynamics, and were not related to pilot behavior. This is seen by noting that the frequency response of normal acceleration to stick deflection should represent aircraft dynamics. Given the linear nature of the fast Fourier transform, a frequency response of stick deflection to normal acceleration should produce the inverse of the aircraft

[3] The experiment in Reference 2 evaluated extremely simple controlled element (aircraft) dynamics such as $1/s$, $1/s^2$, and $1/(s \pm T)$.

dynamics. Thus, the approach used for this project could not be used for pilot compensation analysis as originally expected.

This is further illustrated in Figure L3. This plot presents the stick deflection to normal acceleration frequency response. Note that the coherence is nearly perfect even though the aircraft was flown in a ground simulation mode[4] and the pilot had no normal acceleration cues available. Even attempts to get around this problem using a cross-spectral densities approach were not effective.

The frequency response analysis approach used in this project for the evaluation of pilot compensation on normal acceleration cues was not effective. It produced the frequency response of the aircraft and not the pilot making an examination of pilot compensation impossible. **Do not use the frequency response of stick deflection or force to normal acceleration to evaluate the compensation used by the pilot on normal acceleration cues (R6).**

Ground Simulation

A frequency response analysis of stick deflection and force to tracking error for all ground tracking tasks was performed (objective 3B). As in the airborne cases, the frequency response of stick **deflection** to task error differed from that of the stick **force** to task error only by the frequency response of the stick dynamics. Again, when the stick force frequency response was summed with that of the stick dynamics, the result was the stick deflection to task error frequency response. This result was consistent for all cases.

Two sample frequency analysis plots for the ground evaluation are shown in Figures M1 through M4. For comparison, the same airborne cases flown by the same pilot were provided in Figures K2 and K9 through K11. A preliminary analysis revealed that for all cases the phase, especially at high frequency, was slightly higher on the ground than in the air. There were no consistent trends for the magnitude.

Multi-Axis Tasks

A frequency response analysis of stick deflection and force to tracking error for all of the multi-axis tracking tasks was performed (objective 1B). Several sample frequency response plots for the multi-axis tracking tasks are presented in Appendix M. It is important to note that the frequency response analysis software used for this project required single input, single output systems. Thus, no cross-axis analysis was accomplished and these plots were made by considering one axis at a time. Figures N1 through N8 present sample plots for Cases 1A, 4A, 1D, and 4D.

These plots are nearly identical to those for the single axis cases. For example, Figure N1 presents the frequency response of the pitch axis stick deflection for multi-axis Case 1A. When compared with Figure K4, the gain and phase were nearly identical. However, the coherence of the data drops when moving from the single to the multi-axis

[4] In the ground simulation mode the Lear II computes applicable aerodynamic parameters.

case. This result was consistent for all cases, indicating the non-linear switching of pilot attention between axes.

Conventional Pilot Model Predictions

The dynamics cases described in Appendix D were evaluated using all of the applicable pitch and roll axis pilot models in MIL-STD-1797 (Reference 4). This analysis was accomplished using the handling qualities software included with the data base and described in Appendix G. In addition, a fairly complex optimal pilot model (Reference 8) was used to evaluate the dynamics.

The results of the pitch axis analysis is presented in Table O1. As shown in this table, the MIL-STD-1797A pitch models were unsatisfactory for predicting the handling qualities ratings of the pitch dynamics flown for this evaluation. Three of the five models predicted Level II handling qualities for Case 1 which actually had Level I handling qualities. All of the models predicted Level III handling qualities for Cases 3 and 4 and both of these cases had Level II handling qualities.

The optimal pilot model was moderately successful in predicting the Cooper-Harper ratings, but it is overly complicated and lacks validation[5]. Bode plots of the eighteenth order optimal pilot model predictions and the resulting pilot-aircraft systems are shown in Figures O1 through O4 for Cases 1 and 4. These predicted responses do not resemble the flight test data in Figures K12 and K13. **Develop and validate a less complex optimal pilot model that conforms to the human pilot response data gathered for this project (R7).**

The roll axis pilot model predictions are presented in Table 02. These models successfully predicted the Cooper-Harper ratings and handling qualities levels of the roll axis dynamics evaluated for this project. Due to the simplicity of the MIL-STD-1797A roll axis models, they must be used together to gain adequate insight into an aircraft's predicted handling qualities. The optimal pilot model predictions were slightly pessimistic while the bandwidth criterion predictions were slightly optimistic. However, both were accurate enough to be useful.

[5] This model is described in detail in Reference 8. A brief description is given in Appendix O.

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CONCLUSIONS AND RECOMMENDATIONS

A wide range of aircraft dynamics was evaluated using both single and multi-axis tracking tasks. The experimental setup used was valid and the simulated dynamics and recorded data parameters were validated by analog matching techniques. The data base developed during this project includes valuable flight test data and warrants further examination.

1. **Use the flight test data gathered during this project for further analysis.** (Page 12)

The regulator task was not an acceptable task to use for assigning Cooper-Harper ratings. The magnitude of the task was not high enough to allow the pilot to adequately evaluate the handling qualities of the dynamics cases. As a result, the Cooper-Harper ratings assigned during the regulator task varied excessively.

2. **Do not use the Cooper-Harper ratings assigned during the regulator task for standard pilot opinion rating analysis.** (Page 12)

The product rules used for estimating multi-axis Cooper-Harper ratings from single axis ratings attempt to apply a mathematical operation to the Cooper-Harper rating process and cannot account for the variances that result. The large variance in the product rule predictions evaluated for this project made them useless.

3. **Do not use the product rules in Reference 4 and Appendix I to estimate multi-axis Cooper-Harper ratings from single axis Cooper-Harper ratings.** (Page 13)

The pilot delay during single axis tracking tasks was estimated at 0.27 seconds. The pilot delay times did not vary significantly by pilot or dynamics case. This estimation was consistent with the conventionally accepted value of 0.25 seconds. In all cases, stick deflection lagged stick force by 0.1 ($\pm$0.01) seconds reflecting the lag inherent in the stick dynamics.

4. **When analyzing stick deflection command systems increase the pilot delay values used in pilot models to account for the stick dynamics lag effects.** (Page 14)

The only difference between the frequency response of stick force and stick deflection was the frequency response of the stick dynamics. Because of this, the analysis in this report focused only on stick deflection.

A frequency response analysis of stick deflection to task error revealed that the predicted *pilot* magnitude was consistent with conventional pilot modeling theory.

The phase, however, was not consistent with conventional pilot modeling predictions due to the large amount of phase lead present at higher frequencies. This phase lead was especially noticeable for cases with added delay. For all cases evaluated the pilot response appeared to be strongly related to the aircraft dynamics.

The combined pilot-aircraft system was consistent with theory for both the pitch and roll axes in that the frequency response resembled an integrator near the cross-over frequency. To achieve this combined response, the pilot added more phase lead than possible with a conventional pilot model lead-lag model.

5. **Extend the form of the conventional pilot crossover model to account for pilot response when controlling short period or higher order pitch axis dynamics.** (Page 17)

The frequency response analysis approach used in this project for the evaluation of pilot compensation on normal acceleration cues was not effective. It produced the frequency response of the aircraft and not the pilot making an examination of pilot compensation impossible.

6. **Do not use the frequency response of stick deflection or force to normal acceleration to evaluate the compensation used by the pilot on normal acceleration cues.** (Page 18)

All of the dynamics simulated for this project were evaluated by the pilot models in MIL-STD-1797A and by an optimal pilot model. The roll axis pilot models successfully predicted the Cooper-Harper ratings and handling qualities levels of the roll axis dynamics evaluated for this project. The pitch axis models in MIL-STD-1797A, however, were unsatisfactory for predicting the handling qualities ratings of the pitch dynamics flown for this evaluation. The optimal pilot model was moderately successful in predicting the pitch axis Cooper-Harper ratings, but it was overly complicated and lacked validation.

7. **Develop and validate a less complex optimal pilot model that conforms to the human pilot response data gathered for this project.** (Page 19)

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APPENDIX A

PILOT EXPERIENCE

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PILOT EXPERIENCE

A total of three test pilots were used for this project. Two of the pilots had multi-engine backgrounds and the other pilot had a fighter background. The flight experience of each pilot is summarized below.

Capt Darcy Granley
Canadian Forces

Military Aircraft	Hours
C-130	2250
CC-144	950
CT-114	210
T-38A	40
C-141A	30
CT-134	23
F-16B	10
F-15B	8
A-37	5

Civil Aircraft

Cessna 140	100
Cessna 152	70
Cessna 172	25
DeHavilland Chipmunk	10

Total Flight Hours

Fighter:	273
Multi/Other:	3,503
Total:	3,776

Capt Craig Edkins
United States Air Force

Military Aircraft	Hours
KC-10A	1360
KC-135A	460
T-37B	310
T-38A	190
T-39A/B	125
C-141A	35
F-16B	30
C-23	10
F-15B/D	5
A-37	5
LJ-24	5

Civil Aircraft	Hours
Cessna150/172	200
Piper Arrow	20
Beachcraft Sierra	10
Gliders	5

Total Flight	Hours
Fighter:	670
Multi/Other:	2,120
Total:	2,790

Major Robert R. Sellers
United States Air Force

Military Aircraft	Hours
F-15	1126.5
F-16	562.1
T-38	266.3
F-4	147.6
A/T-37	120.9
C-23	110.7
T-41	21.2
A-7	12.8
KC-135	7.1
NC-131	6.2
UV-18	3.3

Total Flight Hours

Fighter:	2248.2
Multi/Other:	138.2
Total:	2386.4

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APPENDIX B

DETAILED RESEARCH VEHICLE DESCRIPTION

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DETAILED RESEARCH VEHICLE DESCRIPTION

CALSPAN VARIABLE-STABILITY LEAR II

The Calspan Lear II aircraft, shown in Figure B2, was extensively modified for use as an in-flight simulator. An outline of the simulation system is shown in Figure B1. Aircraft models were programmed into the computer's on-board the inflight simulator. Inputs from the pilot through the artificial feel system were fed into the model following system which commanded the Lear II's hydraulically actuated control surfaces to produce the motion of the simulated aircraft.

A digital configuration control system provided the Calspan instructor pilot with an on-line interface This allowed full control of all feel characteristics, command gains, feedback gains, and nonlinear characteristics. For a complete description of the Lear II and its modifications refer to Jane's All the World Aircraft (Reference 6) and AIAA Paper 93-3606, August 93 (Reference 7).

Real time monitoring of up to 64 selected parameters at a sampling rate of 100 hertz was possible. The aerodynamic rates, p, q, and r, were measured directly from rate gyros and normal accelerations were measured by accelerometers located in the belly of the aircraft near the nominal center of gravity. These sensors were located approximately 13.6 feet aft of the pilot. The data were stored on 90 megabyte personal computer (PC) compatible, removable Bernoulli drive cartridges.

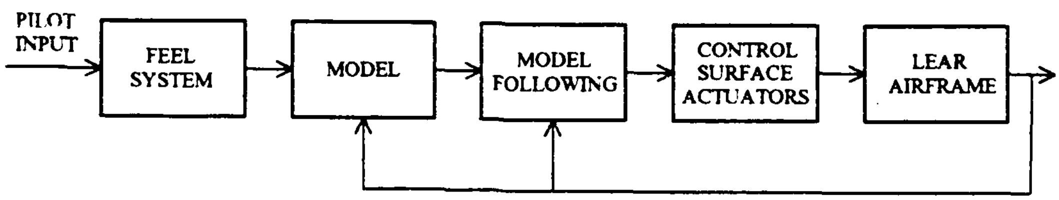

Figure B1: Inflight Simulation Block Diagram

MODEL FOLLOWING SYSTEM

The aircraft model-following system was an implicit three axis system. The measured Lear II states were used to compute the desired model accelerations. The Lear II was then forced to have the same accelerations as this model. The system automatically compensated for Lear II fuel burn by computing the moments of inertia and center of gravity, and using these quantities in the model-following equations.

DIGITAL COMPUTER SYSTEM

The digital computer system was hosted in a twenty slot, passive Industry Standard Architecture (ISA) backplane located in the main cabin. The host processor was a single-board 33 MHz 80486 computer with 8 megabytes of random access memory (RAM). The main simulation control program ran under MS-DOS on the host processor and allowed the monitoring or changing of any model or feel system characteristic at any time, including the simulation and recording of inflight data.

FEEL SYSTEM

The feel system was hydraulically powered, electrically varied, and included a center-stick controller. The variable feel system provided the pilot with the desired control forces, displacements, and gradients. The feel system model was programmed through the digitally controlled simulation computer. Circuitry between the feel system and the flight control system allowed the insertion of lead/lag, transport time delay, and freeplay between the cockpit control input and control surface motion. In addition, the feel system frequency and damping ratio, as well as, the force gradient could be varied in flight.

COLOR FLAT PANEL DISPLAY

A Color Flat Panel display was located on the main instrument panel in front of the evaluation pilot's position. The display is shown in Figure B3. Pitch and roll errors were indicated to the pilot by the angular deviation between the command bar and the extended fixed-pipper attitude reference. The lengths of the subtends on the attitude reference correspond to 0.5 degree of pitch error and 5 degrees of roll error. A horizon line was also displayed to reduce the potential for pilot disorientation. The screen components sensed the airplane's attitude, filtered and conditioned the signal by removing noise and structural interactions, performed anti-aliasing, quantified the digital inputs, calculated the task commands and error signals, and projected these quantities onto the screen. A 0.025 second delay arose from this process.

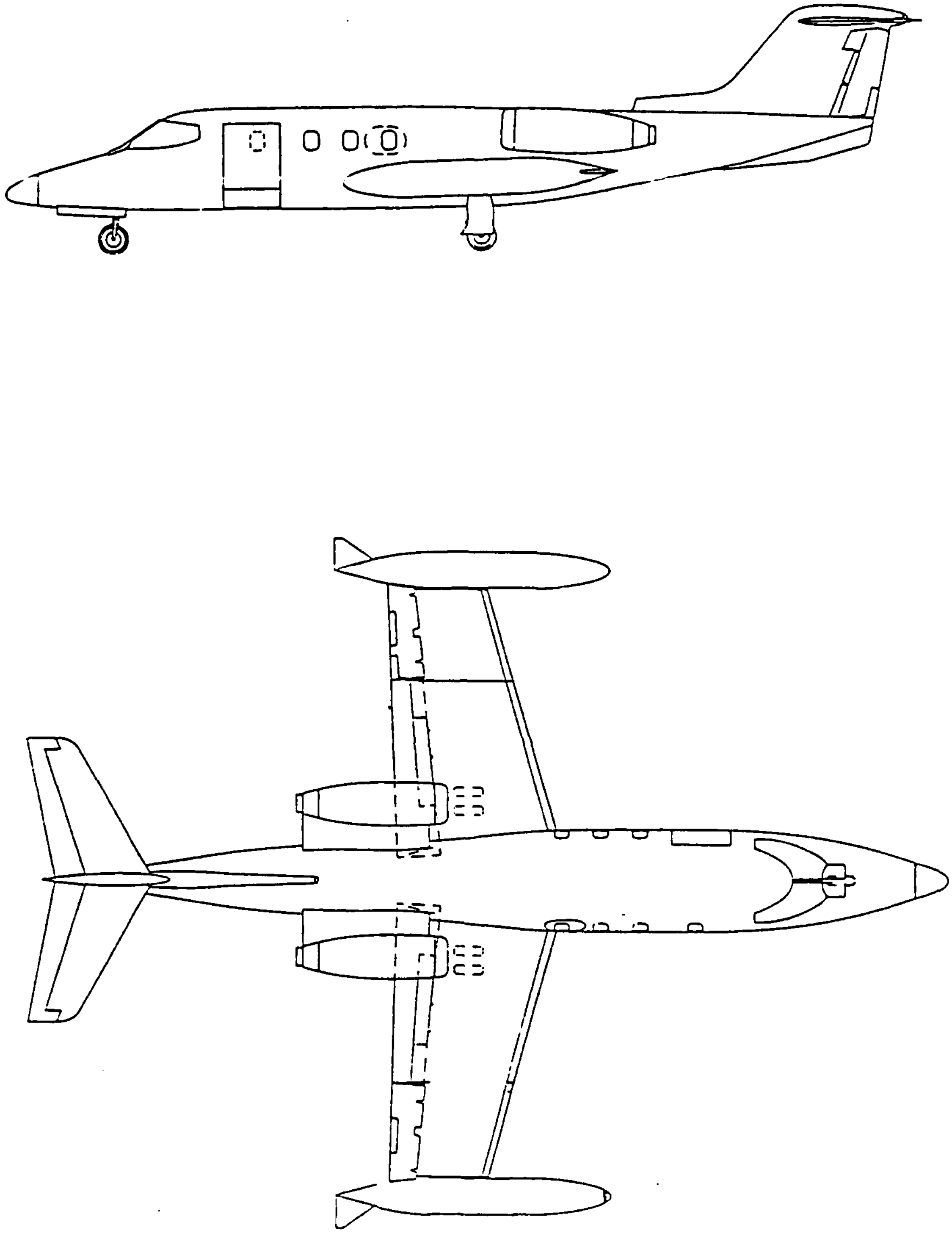

Figure B2: Two Plan View of Lear 25B

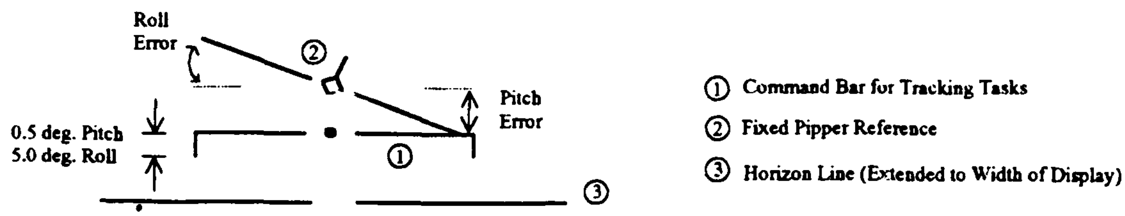

Figure B3: Color Flat Panel Display

The Learjet 25 operating limitations are presented in Table B1 below.

Table B1: Learjet 25 Operating Limitations

SPEEDS	
V_{MO} Sea Level to 14,000 ft	306 KIAS
V_{MO} Above 14,000 ft	359 KIAS
M_{MO}	0.82 M
M_{MO} With Autopilot OFF	0.78 M
WEIGHT LIMITS - VSS FLIGHTS	
Ramp	15,500 lb
Takeoff	15,000 lb
Landing	13,300 lb
FUEL	
Wings	24512lb
Tips	2425 lb
Fuselage	1307 lb
Total	6144 lb
Max Tip Tank Fuel for Landing	800 lb each
LOAD LIMITS	
Flaps Up	+ 4.0 to -1.0 g

The Learjet 25 safety trips parameters are presented in Table B2 below.

Table B2: Learjet 25 Safety Trips

PARAMETER	TRIP LEVEL
Manual Initiation	--
Computer Control System Error	Discrete
Surface SERVO Commanded Rates -Elevator -Aileron -Rudder	 100 deg/sec 200 deg/sec 200 deg/sec
Normal Acceleration	+ 2.8 g (max) + 0.15 g (min)
Lateral Acceleration	± 0.3 g
Angle of Attack	± 10 deg (max) - 5 deg (min)
Maximum Sideslip Limit	± 15 deg

Table B3: Calspan Lear 25 Sensor Accuracies and Resolutions

PARAMETER	UNITS	SENSOR ACCURACY AT PILOT POSITION	SENSOR RESOLUTION	ANALOG/ DIGITAL RESOLUTION	RECORDING RESOLUTION
F_{as}	lb	0.25±2% of Reading	Continuous	0.0488	0.003125
F_{es}	lb	0.25±2% of Reading	"	0.0488	0.003125
F_{rp}	lb	0.25±2% of Reading	"	0.0977	0.00625
δ_{as}	in	see Note 7	"	0.0024	0.0003125
δ_{es}	in	see Note 7	"	0.0024	0.0003125
δ_{rp}	in	see Note 7	"	0.0012	0.000625
θ	deg	see Note 4	"	0.0439	0.001400625
ϕ	deg	see Note 4	"	0.0439	0.005625
p	deg/sec	see Note 1	0.01	0.0488	0.003125
q	deg/sec	see Note 1	0.01	0.0195	0.00125
r	deg/sec	see Note 1	0.01	0.0195	0.00125
n_x	G	see Note 2	see Note 2	0.0005	0.00003125
n_y	G	see Note 2	see Note 2	0.0005	0.00003125
n_z	G	see Note 2	see Note 2	0.0024	0.00015625
V_{IAS}	knots	see Note 5	Continuous	0.305	0.00625
OAT	deg K	± 2	"	0.0488	0.003125
PA	ft	see Note 6	"	19.5	0.625
α	deg	see Note 3	see Note 3	0.0098	0.000625
β	deg	see Note 3	see Note 3	0.0098	0.000625
δ_e	deg	see Note 7	Continuous	0.0098	0.000625
δ_a	deg	see Note 7	"	0.0195	0.00125
δ_r	deg	see Note 7	"	0.0195	0.00125

Accuracy of each recorded parameter

Note 1:
p ±100 deg/sec Full scale
q ±40 deg/sec Full scale
r ±40 deg/sec Full scale
Linearity to 1/2 Full scale ±0.5% of Full Scale
Linearity to Full scale ±2% of Full Scale
Hysterisis 0.3% Full Scale
Threshold 0.01 deg/sec

Note 2:
n_x ± 1 g Full Scale
n_y ± 1 g Full Scale
n_z ± 1 g Full Scale
Resolution 0.001% of Full Scale
Hysterisis 0.02% of Full Scale
Nonlinearity 0.05% of Full Scale

Note 3:
α and β (scaled ± 20°)
Mechanical 56 deg ± 2 deg
Electrical 50 deg ± 2 deg
Static accuracy ± 1% of Full Scale at 90 KIAS
Potentiometer Resolution ±0.18% of Full Scale
Potentiometer Linearity ±0.5% of Full Scale

Note 4: Sensor Accuracy
θ and ϕ are computed by $\tan^{-1}$(sin/cos)
θ and ϕ resolved to sin-cos
erection accuracy ±1%

Note 5: Dynamic Pressure

Repeatability	±0.02% of Design Pressure Range
Hysterisis	±0.015% of Design Pressure Range
Nonlinearity	±0.1% of Calibrated Pressure Span
Accuracy	±0.5% of Calibrated Pressure Span

Note 6: Static Pressure

Resolution	5 ft @ Sea Level 6 ft @ 50,000 ft.
Repeatability	5 ft @ Sea Level 20 ft @ 50,000 ft.
Hysterisis	5 ft @ Sea Level 20 ft @ 40,000 ft.
Accuracy	±0.4% of Reading plus 25 ft.

Note 7: Sensor Accuracy
DC - DC LVDT ± 1 in Stroke δ_{as},δ_{es},δ_{rp},δ_e,δ_a,δ_r
Linearity 0.5% of Full Scale over total work range
Linearity 1.0% of Full Scale over max usable range

APPENDIX C

TRACKING TASK DESCRIPTION

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TRACKING TASK DESCRIPTION

GENERAL

Three different types of tracking tasks were used for this test, a discrete tracking task, a sum-of-sines tracking task, and a regulator task. To lessen the pilot's ability to memorize the tasks, two different tasks of each type were used during testing. Each task was 53 seconds long. The tasks are described in the following paragraphs.

DISCRETE TRACKING TASK

This task consisted of a series of steps and ramps similar to the one illustrated in Figure C-1. The initial command in each axis was a step. The maximum commanded input was ±2.25 degrees from the initial condition in pitch and ±35 degrees in roll.

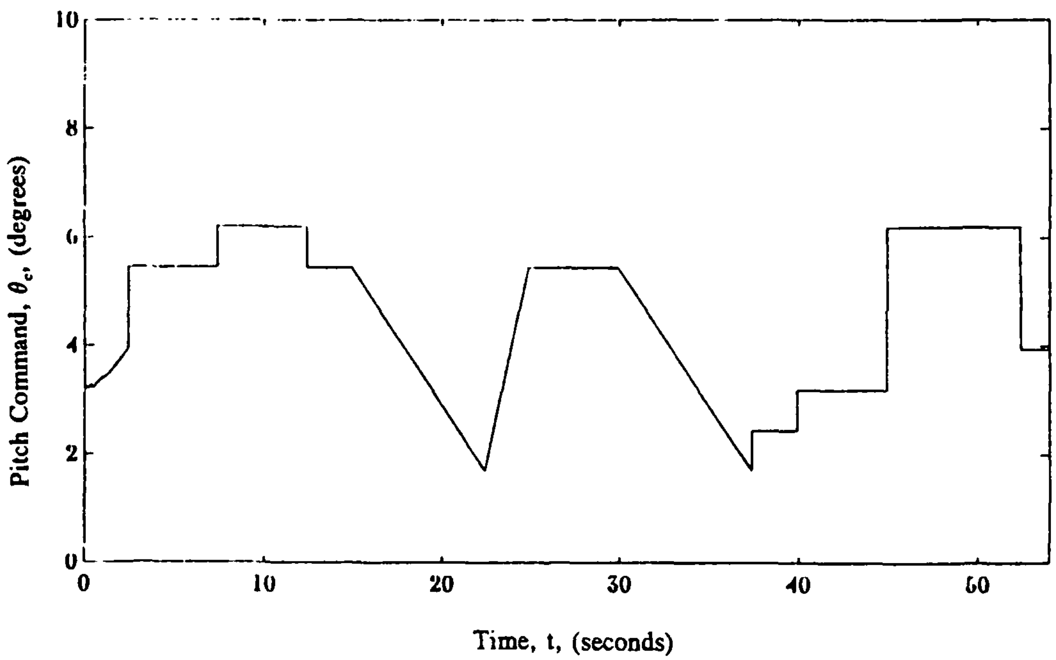

Figure C1: Discrete Pitch Tracking Task

SUM-OF-SINES TRACKING TASK

The sum-of-sines tracking task was a random appearing, frequency-based function computed using the following formula:

$$\theta_c = K \cdot \sum_{i=1}^{n} A_i \sin(\omega_i t + \phi_i)$$

The tasks used in this test were formed by summing 13 sine waves. The phases (ϕ_i) were randomly chosen and the task gain, K, was set to achieve the desired task amplitude. The frequencies (ω_i) were evenly spaced between 0.1 and 30 radians per second. The amplitudes (A_i) were selected using a corner frequency of 2 radians per second and a second-order roll off producing the power spectral density magnitudes shown in Figures C3. A typical task is shown in Figure C2. While this task appeared random, the power spectral density was concentrated only at the selected frequencies (ω_i) as shown in Figure C3.

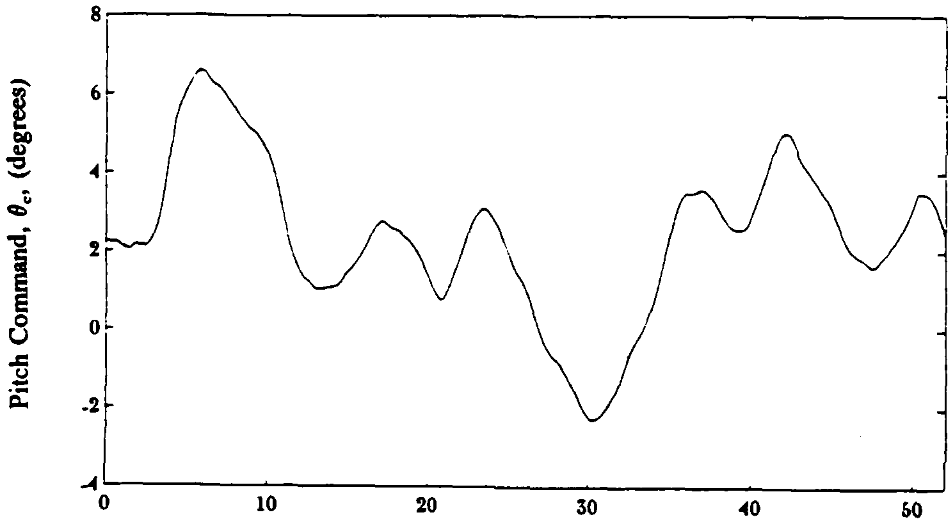

Figure C2: Sum-of-Sines Pitch Tracking Task

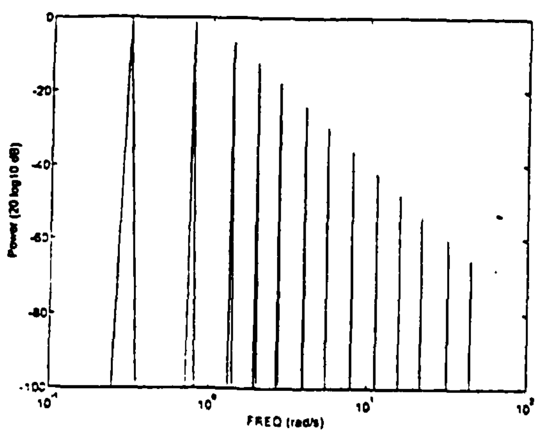

Figure C3: Power Spectral Density of Sum-of Sines Tracking Task

REGULATOR TASK

The regulator task was computed in the same manner as the sum-of-sines task. Instead of driving a command bar, however, this task was input as an additive to the pilot's stick command. It had the effect of simulating turbulence. The pilot's objective during this task was to maintain wings level, zero pitch flight. This tracking task had the same frequency content as the sum-of-sines task.

DESIRED AND ADEQUATE CRITERIA

Each airborne test case was examined using all three types of tracking tasks. Only the discrete and sum-of-sines tracking tasks were used during ground simulation runs. Cooper-Harper ratings were assigned for each run in accordance with the following criteria:

DESIRED CRITERIA: Pilot induced oscillations (PIO) tendencies do not compromise tracking task. Commanded attitude maintained within 0.5 degrees in pitch and 5 degrees in bank (measured at end of command bar) for 50% of the time except immediately following step command changes. See Figure C4 below.

ADEQUATE CRITERIA: Commanded attitude maintained within 1 degrees in pitch and 10 degrees in bank (measured at end of command bar) for 50% of the time except immediately following step command change.

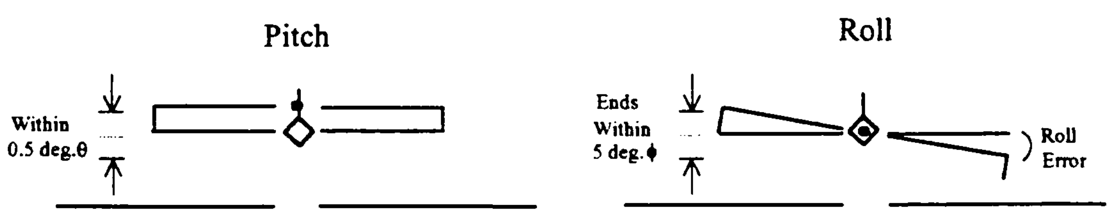

Figure C4: Desired Criteria

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APPENDIX D

AIRCRAFT DYNAMICS

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AIRCRAFT DYNAMICS CASES

The following dynamics were selected based on past Calspan flight test experience so that Case 1A would produce a level 1 aircraft. Subsequent cases degraded either the damping, roll mode time constant, or system delay to produce the desired spread in aircraft handling qualities.

Longitudinal Cases (θ/δ_e):

Case 1

$$\frac{20(s+1.8)e^{-0.04s}}{s(s^2+8.4s+36)}$$

Case 2

$$\frac{20(s+1.8)e^{-0.04s}}{s(s^2+4.8s+36)}$$

Case 3

$$\frac{20(s+1.8)e^{-0.24s}}{s(s^2+8.4s+36)}$$

Case 4

$$\frac{20(s+1.8)e^{-0.24s}}{s(s^2+4.8s+36)}$$

Lateral Cases (ϕ/δ_a):

Case A

$$\frac{2.5e^{-0.04s}}{s(s+2.5)}$$

Case B

$$\frac{e^{-0.04s}}{s(s+1)}$$

Case C

$$\frac{2.5e^{-0.24s}}{s(s+2.5)}$$

Case D

$$\frac{e^{-0.24s}}{s(s+1)}$$

Table D1: Case Definition Table

CASE	Longitudinal		Lateral		CASE	Longitudinal		Lateral	
#	ζ_{sp}	τ_e[1]	τ_R	τ_e[1]	#	ζ_{sp}	τ_e[1]	τ_R	τ_e[1]
1	0.7	0.04			2A	0.4	0.04	0.4	0.04
2	0.4	0.04			2B	0.4	0.04	1.0	0.04
3	0.7	0.24			2C	0.4	0.04	0.4	0.24
4	0.4	0.24			2D	0.4	0.04	1.0	0.24
A			0.4	0.04	3A	0.7	0.24	0.4	0.04
B			1.0	0.04	3B	0.7	0.24	1.0	0.04
C			0.4	0.24	3C	0.7	0.24	0.4	0.24
D			1.0	0.24	3D	0.7	0.24	1.0	0.24
1A	0.7	0.04	0.4	0.04	4A	0.4	0.24	0.4	0.04
1B	0.7	0.04	1.0	0.04	4B	0.4	0.24	1.0	0.04
1C	0.7	0.04	0.4	0.24	4C	0.4	0.24	0.4	0.24
1D	0.7	0.04	1.0	0.24	4D	0.4	0.24	1.0	0.24

[1] The minimum Lear II simulation delay is 0.04 seconds

DIRECTIONAL DYNAMICS

During airborne simulation in Lear II, sideslip angle rate ($\dot{\beta}$) was driven to zero by the simulation computers. Additionally, the roll and yaw axes were de-coupled so the pilot could fly the simulations with feet on the floor.

ACTUATOR DYNAMICS

Elevator: Aileron:

$$\frac{70^2}{s^2+2(.7)(70)s+70^2} \quad \textit{and} \quad \frac{70^2}{s^2+2(.7)(70)s+70^2}$$

STICK DYNAMICS

Longitudinal: Lateral:

$$\frac{16^2}{s^2+2(.7)(16)s+16^2} \quad \textit{and} \quad \frac{16^2}{s^2+2(.7)(16)s+16^2}$$

STICK FEEL SYSTEM CHARACTERISTICS

	Elevator:	Aileron:
Stick Force Gradient	6 lb/in	6 lb/in
Stick Breakout Force	0.75 lb	0.75 lb
Stick Force per g	7 lb/g	---------
Control Gearing	8 deg/in	12 deg/in

IMPLEMENTATION

The dynamics described above were implemented as a stick position command system as shown in Figures D1 and D2.

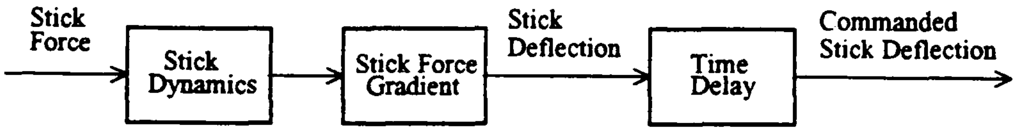

Figure D1: Feel System

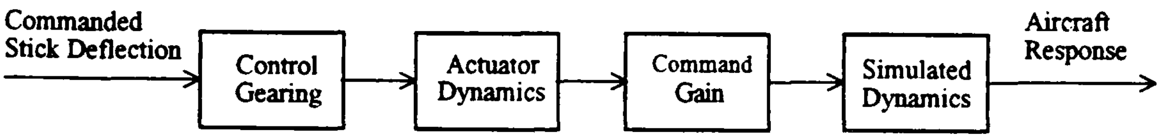

Figure D2: Flight Control System

Using the analog matching technique described in the results section of this report, the following equations represent the linear implementation of these dynamics[1]:

Pitch Axis Implementation:

$$\frac{\theta}{F_{es}} = \frac{16^2}{[.7,16]} \cdot \frac{1}{6} \cdot 8 \cdot \frac{70^2}{[.7,70]} \cdot \frac{5.5(2+1.8)}{s[\zeta,6]} e^{-\tau_D s}$$

$$\frac{\theta}{\delta_{es}} = 8 \cdot \frac{70^2}{[.7,70]} \cdot \frac{5.5(s+1.8)}{s[\zeta,6]} e^{-\tau_D s}$$

[1] "[.7,16]" denotes $[\zeta,\omega_n]$ as in $s^2 + 2\zeta\omega_n s + \omega_n^2$

Roll Axis Implementation:

$$\frac{\phi}{F_{as}} = \frac{16^2}{[.7,16]^1} \cdot \frac{1}{4} \cdot 12 \cdot \frac{70^2}{[.7,70]} \cdot \frac{3.3}{s(s+T_R)} e^{-\tau_D s}$$

$$\frac{\phi}{\delta_{as}} = 12 \cdot \frac{70^2}{[.7,70]} \cdot \frac{3.3}{s(s+T_R)} e^{-\tau_D s}$$

DYNAMICS VALIDATION

Figures D3 through D6 present the time histories of the actual aircraft response and the predicted aircraft response formed by simulating the above implementations on MatLab.

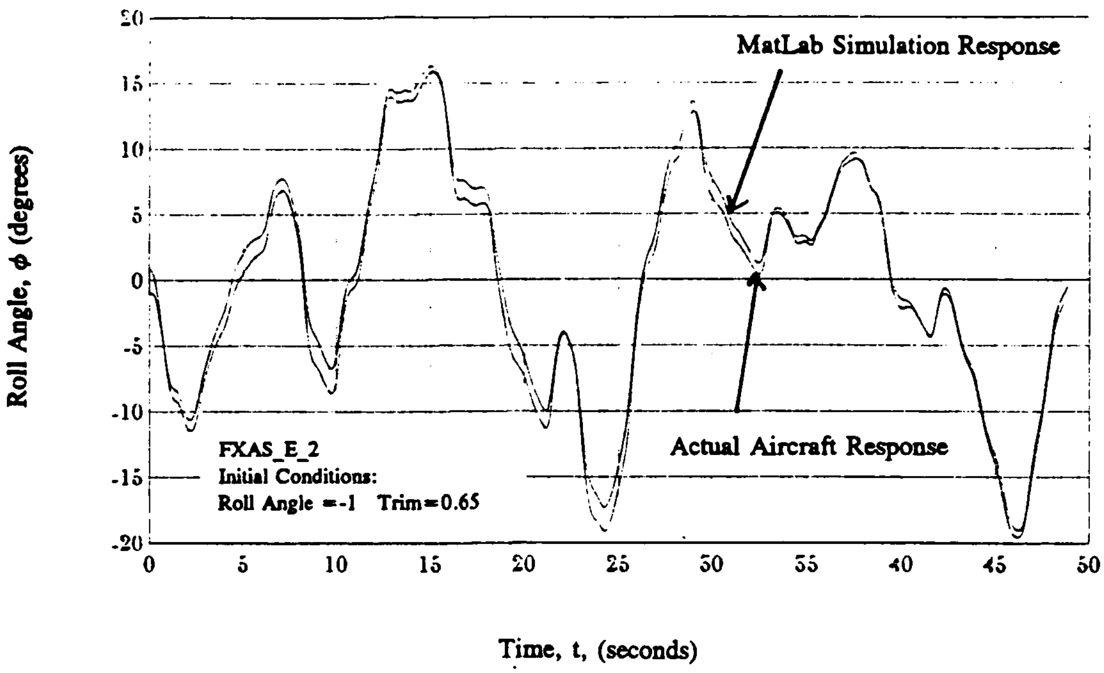

Figure D3: Analog Matching of Case A - Stick Force to Roll Angle

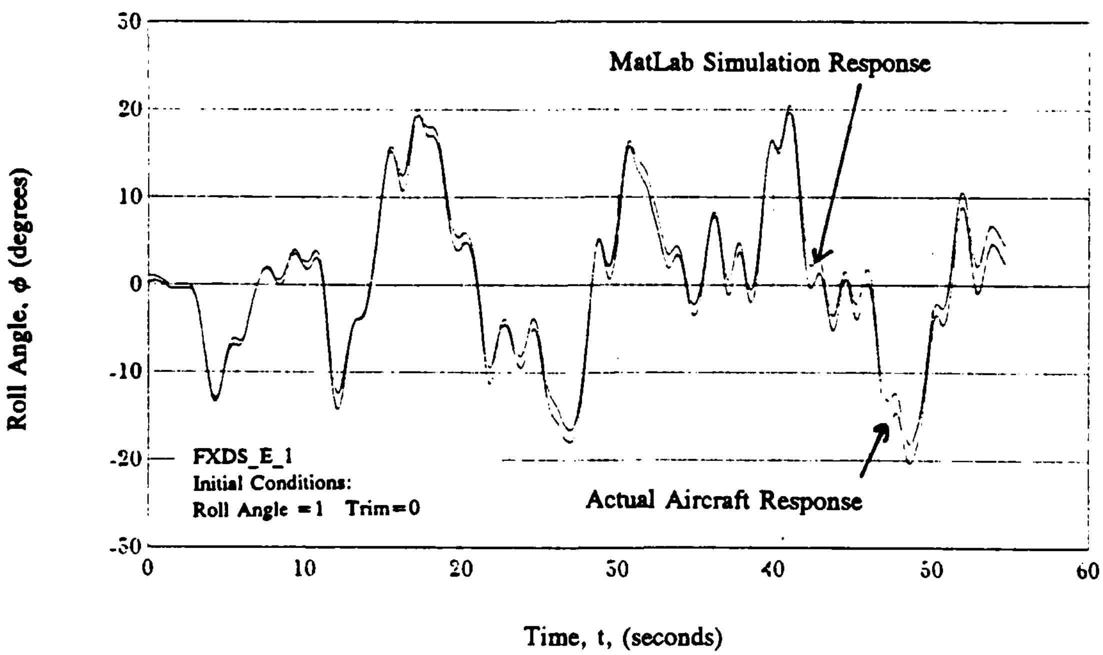

Figure D4: Analog Matching of Case D - Stick Deflection to Roll Angle

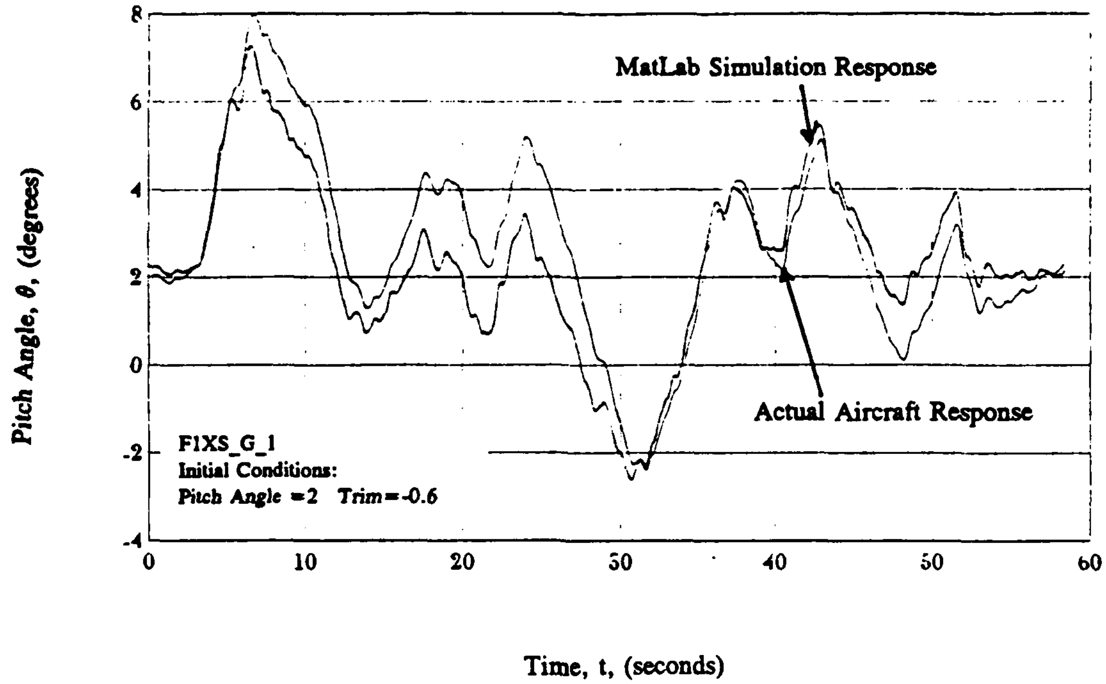

Figure D5: Analog Matching of Case 1 - Stick Force to Pitch Angle

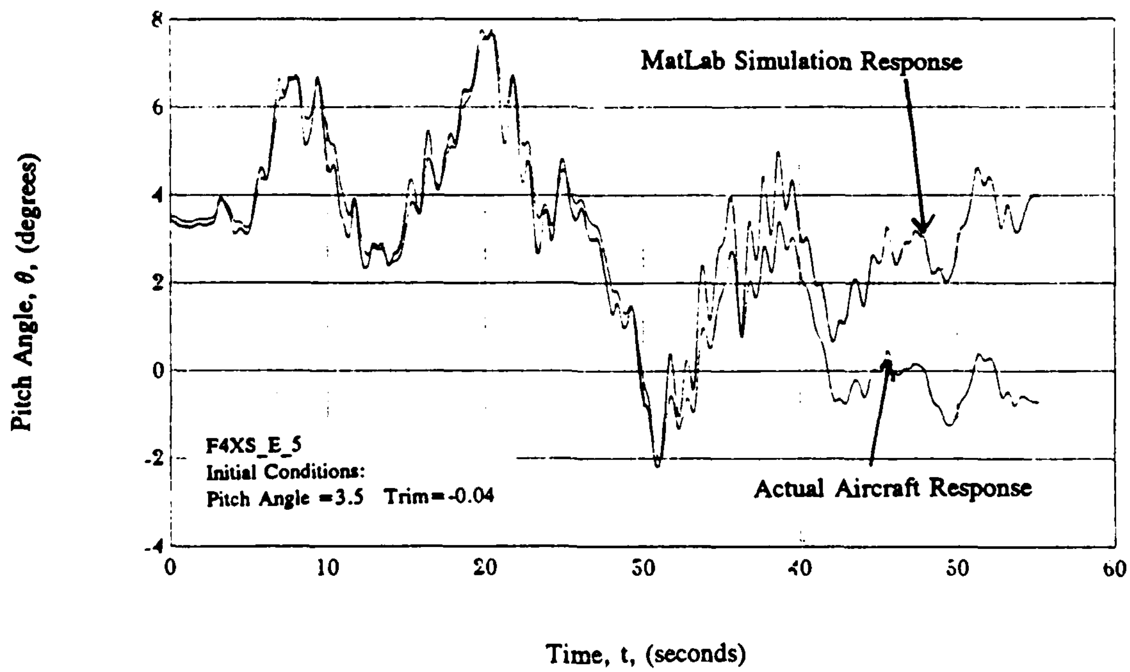

Figure D6: Analog Matching of Case 4 - Stick Deflection to Pitch Angle

APPENDIX E

DATA REDUCTION SOFTWARE

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DATA REDUCTION SOFTWARE

FREQUENCY RESPONSE ANALYSIS

General

As explained in the Test and Evaluation section of this report, a frequency response analysis of task error to pilot response was performed to provide insight into human pilot behavior. Data collected during this test was in the time domain. To convert this data to the frequency domain, a Fourier transform was used. The following paragraphs briefly explain the basics of the fast Fourier transform and describe the MatLab software used for data reduction. This software is included in the data base produced by this report.

Fast Fourier Transform

The purpose of any Fourier transform is to convert time domain data to frequency domain data. In doing so, this transformation yields power spectral densities for both the input and output of the transfer function, a Bode plot of the transfer function, and a coherence function. The power spectral densities represent the magnitude of the input and output parameters as a function of frequency. The Bode plot depicts the magnitude and phase of the transfer function versus frequency. Finally, the coherence function provides a measure of how much of the output at each frequency is caused by the input rather than noise or other inputs. A coherence value of 1.0 means that the output is completely a function of the input, whereas a value of 0.0 means that the output is completely a function of noise. A coherence value of greater than 0.8 is necessary to produce a valid linear transfer function of the response.

A common technique used by the Air Force Flight Test Center (AFFTC) in performing frequency response analysis is ensemble averaging. Ensemble averaging improves the reliability of frequency response calculations for time histories of data corrupted by measurement noise (which is the case in flight test). Overlap ensemble averaging was used for this report. When using overlap ensemble averaging, a long time history is divided into sequential parts. Each of these overlapping parts is Fourier transformed and averaged. Based on the mathematical derivations in Reference 9, the standard practice at the AFFTC is to restrict the permissible overlap to no more than 66 percent of the length of a time history. For example, if a 45 second time history is divided into overlapping time histories of 10.24 seconds each, no more than 0.66 (10.24)=6.76 seconds would be overlapped. Fifty percent overlap was used for this project.

MatLab Frequency Response Analysis Software Description

The MatLab frequency response analysis program used for this test, was written by Captain Mary Manning, USAF TPS/TS. It was created using government resources and can be copied and distributed freely. It consisted of 7 sub-programs or *m-files*. The two main files used for data reduction were the FRAPREP.M and FRA.M files.

The FRAPREP.M file is a series of MatLab commands designed to pre-process the time domain data for FRA.M. It offers the user several options such as windowing, overlap, and zero filling and creates the ensembles for FRA.M. The command line for FRAPREP.M is:

[x,y]=fraprep(m,n,x1,y1,x2,y2,x3,y3,x4,y4,...x9,y9)

m is the desired size of each ensemble as well as the size of the fast Fourier transform to be used in FRA.M. ***n*** is the number of ensembles to be created for processing by FRA.M (the maximum number of ensembles allowed by the program is nine). ***x1*** and ***y1*** are the first input/output pair. ***x2*** and ***y2*** are the second input/output pair. ***x2***, ***y2***, and the remaining ***x***, ***y*** pairs are optional entries. The output vectors, ***x*** and ***y***, contain the resulting vectors after overlapping.

The FRA.M file contains a series of MatLab commands that calculate the input and output power spectral densities, the transfer function magnitude and phase, and the coherence of at least two sets of input and output data. Once these calculations are performed, FRA.M plots the transfer function's magnitude, phase, and coherence as a function of frequency. The command line for FRA.M is:

[F,P,T]=FRA(X,Y,M,SRATE,BOUND)

X and **Y** are the output arguments from the FRAPREP.M program. **M** is the number of points in each ensemble (**M** must be a power of two). **BOUND** is the desired confidence level for the statistical bounds. **BOUND** defaults to 0.95 if no value is entered. FRA.M calculates confidence bounds using the CHI squared distribution. This calculation is valid if no overlapping of data were used in the FRAPREP portion of processing. The calculation becomes an approximation if data overlap was used. This approximation is reasonable if the overlap is less than 67 percent. The output argument, F, contains the frequency vector. **P** consists of vectors describing the power spectral density of the input and output. **SRATE** is the sampling rate in samples per second. **T** contains the transfer function magnitude, phase, and coherence vectors.

MatLab Frequency Response Analysis Software Validation

The MatLab frequency response analysis software was based on the theory developed in *Spectral Analysis and Its Applications* (Reference 9) and the Air Force Flight Test Center (AFFTC) frequency response analysis code developed for the AFFTC CYBER computer system. This code was developed by Mr. Bill Kiddo and Mr. Tom Twisdale and was previously validated by the AFFTC. To validate the MatLab version, data from the ground simulations at Edwards AFB were analyzed using both the MatLab and CYBER versions. The output vectors from each were then compared. For the frequency range of interest (0.1 to 10 hertz), the results agreed to within 0.1 percent. Thus, the MatLab frequency response analysis code was assumed valid and acceptable for use in this test project.

Frequency Response Analysis Steps

The following steps were followed to perform the frequency response analyses of the Lear II ground and airborne simulation test data.

Step 1: The data file (*.mat) for the particular run was loaded into MatLab using the following command:

load *filename*

Step 2: The Lear II digital computer file was broken into named vectors containing the parameters listed in Table G1 using the file DATAREAD.M developed by Calspan:

dataread

Step 3: Seven ensembles were created for processing by the FRAPREP.M file using the following MatLab commands. The first ensemble began with sample 501, or 5 seconds into the task. The following example is for longitudinal stick deflection to normal acceleration.

```
des1=des(501:1524);
des2=des(1013:2036);
des3=des(1525:2548);
des4=des(2037:3060);
des5=des(2549:3572);
des6=des(3061:4084);
des7=des(3573:4596);
nz1=nz(501:1524);
nz2=nz(1013:2036);
nz3=nz(1525:2548);
nz4=nz(2037:3060);
nz5=nz(2549:3572);
nz6=nz(3061:4084);
nz7=nz(3573:4596);
```

Step 4: The frequency response data were processed using the FRAPREP.M file. The command line for invoking FRAPREP.M was:

```
[xprep yprep]=fraprep(1024,7,nz1,des1,nz2,des2,
nz3,des3,nz4,des4,nz5,des5,nz6,des6,nz7,des7)
```

Step 5: The input and output power spectral densities, the transfer function magnitude and phase, and the coherence of the input and output data were plotted using the FRA.M file. The command line for invoking FRA.M was:

```
[f,p,t]=fra(xprep,yprep,1024,100);
```

APPENDIX F

TEST POINT EVALUATION CARDS

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HAVE PILOT TEST CARD									
CASE #	Itera-tion #	Sortie #	Longitudinal		Lateral		Pilot	Date	Filename
			ζ_{sp}	τ_e	τ_R	τ_e			
Discrete									

PRE-BRIEF

All test points start at 15,000 feet MSL, 250 KIAS

The pilot will perform each task using any pilot compensation necessary to minimize the average tracking task error.

DESIRED: PIO tendencies do not compromise tracking task. Commanded attitude maintained within 0.5 degrees in pitch and 5 degrees in bank (measured at end of command bar) for 50% of the task except immediately following step command changes.

ADEQUATE: Commanded attitude maintained within 1 degree in pitch and 10 degrees in bank (measured at end of command bar) for 50% of the task except immediately following step command change.

POST-BRIEF

C-H Rating	PIO Rating

1. Assign PIO rating

2. Assign Cooper-Harper rating

3. Aircraft response to input (pitch/roll)

    Initial - Quick, Slow, Sluggish, etc

    Final - Predictable, Crisp, etc

4. Does the level of aggressiveness affect task performance (precision, accuracy, etc)?

5. Any special piloting techniques/compensation required?

6. Any undesirable aircraft motions (turbulence, disorienting)?

7. Provide actual percentage performance to pilot

8. Review Cooper-Harper rating

Turb Rating	% in Desired	% in Adequate	C-H Re-Rating

Figure F1: Test Point Evaluation Card

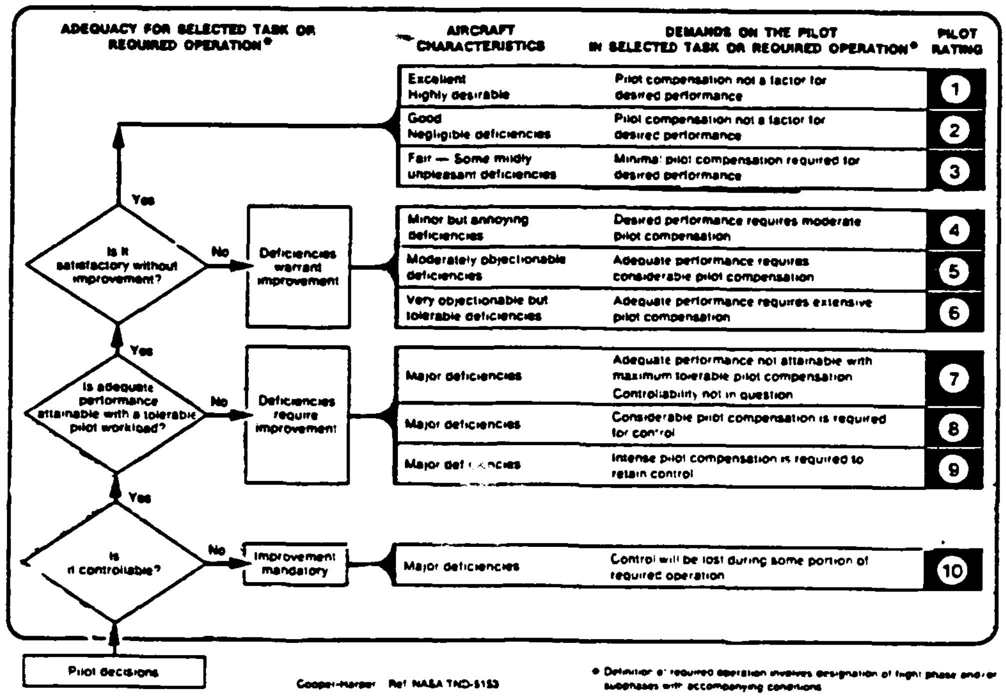

Figure F2: Cooper-Harper Handling Qualities Rating Scale

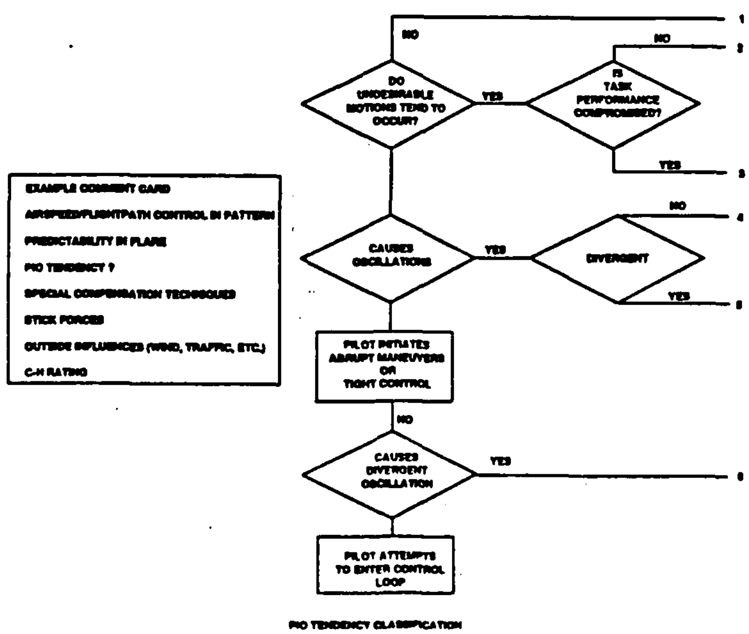

Figure F3: Calspan Pilot Induced Oscillation Rating Scale

Table F1 - Turbulence Rating Scale

INCREASE OF PILOT EFFORT WITH TURBULENCE	DETERIORATION OF TASK PERFORMANCE WITH TURBULENCE	RATING
No Significant Increase	No Significant Deterioration	A
More Effort Required	No Significant Deterioration	B
	Minor	C
	Moderate	D
Best Efforts Required	Moderate	E
	Major (But Evaluation Tasks Can Still Be Accomplished)	F
	Large (Some Tasks Cannot Be Performed)	G
Unable to Perform Tasks		H

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APPENDIX G

DATA BASE DESCRIPTION

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DATA BASE DESCRIPTION

The data base built by this report includes the following items:

1) Flight test data in MatLab format for each run

2) DATAREAD.M processes the flight test data

3) Scoring variables for each run

4) Video tape records

5) Calibration flight data

6) Frequency response analysis programs used for this project

7) Handling Qualities Toolbox (MatLab program) used to determine MIL-STD-1797A pilot model predictions)

The programs in 5 and 6 above consisted of MatLab.M files. They were developed using government resources and can be copied and distributed freely. All of the above items fit onto one 90 megabyte Bernoulli cartridge. A detailed description of the above items is given below.

1. **Flight Test Data**: These files are stored in MatLab data file (.MAT) format. The file name conventions is as follows:

F	4B	S___	E___	1
F for Flight G for Ground Simulation	CASE (X Denotes Single Axis Case)	TASK TYPE S=Sum-of-Sines D=Discrete R=Regulator	Pilot Initial	Flight or Simulation #

For example, using this convention the file FXAD_G_3 contains the flight test data from the airborne (flight) simulation of single axis Case A, discrete tracking task, flown by pilot "G" on flight number 3.

After each file is loaded into MatLab, the file "DATAREAD.M" is used to break the data into individual vectors by variable name. The following variables were recorded at 100 samples per second.

Table G1: Data File Variable Definitions

VARIABLE	DEFINITION	VARIABLE	DEFINITION
HOURS	-	fes	force elevator stick
MINUTES	-	frp	force rudder pedal
SECONDS	-	h_p	pressure altitude
MSECONDS	milliseconds	nx	normal acceleration x direction
alpha_cf	alpha	ny	normal acceleration y direction
beta_cf	beta	nz	normal acceleration z direction
da	aileron deflection	oat_k	outside air temperature (kelvin)
das	aileron stick deflection	p	roll rate
das_err	aileron stick deflection error	phi	roll angle
de	elevator deflection	phi_cmd	roll command
des	elevator stick deflection	q	pitch rate
des_err	elevator stick deflection error	r	yaw rate
dr	rudder deflection	theta	pitch angle
drp	rudder pedal deflection	theta_cmd	pitch command
ds	stick deflection	time	-
engaged	variable stability on/off	v_ias	indicated airspeed
fas	force aileron stick		

2. **DATAREAD.M**: This file, written by Calspan and modified by the test team, was used to process the flight test data prior to analysis. This program primarily breaks the flight test data into individual vectors by variable name. The test team modified this file to correct two deficiencies in the test data. First normal acceleration is multiplied by "-1" so that a positive pitch produces a positive normal acceleration (n_z). Second, the stick deflection in the data files is actually *commanded* stick deflection and was measured after the time delay in Cases 3, 4, C, and D. Thus, for Cases 3, 4, C, and D the stick deflection vector was shifted by 20 samples or 0.2 seconds, so that the resulting vector now represents actual stick deflection.

3. **Scoring Variables**: The Lear II simulator computer was used to compute the percentage of time desired and adequate criteria were met. Several other scoring variables described in Table G2 were recorded and stored in ".M" files. By typing the file name (for example, FXAD_G_3) at the MatLab command prompt, all of the variables listed in Table G2 can be loaded for a given run. The file name convention used was the same as that described above.

Table G2: Scoring Variables Descriptions

VARIABLE	DESCRIPTION
trs_cum_phi_cmd	Cumulative Roll Command
trs_cum_phi_cmd_sq	Cumulative Roll Command Squared
trs_cum_phi_err	Cumulative Roll Error
trs_cum_phi_err_sq	Cumulative Roll Error Squared
trs_cum_theta_cmd	Cumulative Pitch Command
trs_cum_theta_cmd_sq	Cumulative Pitch Command Squared
trs_cum_theta_err	Cumulative Pitch Error
trs_cum_theta_err_sq	Cumulative Pitch Error Squared
trs_pct_adequate	Cumulative Percentage in Adequate Region
trs_pct_desired	Cumulative Percentage in Desired Region
trs_phi_adequate_tol	Tolerance for Adequate Roll Region
trs_phi_cmd_mean	Mean Roll Command
trs_phi_cmd_rms	Root Mean Square of Roll Command
trs_phi_desired_tol	Tolerance for Desired Roll Region
trs_phi_err_mean	Mean Roll Error
trs_phi_err_rms	Root Mean Square of Roll Error
trs_phi_nrmse	Normalized Root Mean Square of Roll Error
trs_phi_pct_adequate	Cumulative Percentage in Adequate Roll Region
trs_phi_pct_desired	Cumulative Percentage in Desired Roll Region
trs_phi_tot_adequate	Cumulative Time in Adequate Roll Region
trs_phi_tot_desired	Cumulative Time in Desired Roll Region
trs_scoring_n	Number of Scoring Samples
trs_scoring_timer	Total Time for Scoring during Each Task
trs_theta_adequate_tol	Tolerance for Adequate Pitch Region
trs_theta_cmd_mean	Mean Roll Command
trs_theta_cmd_rms	Root Mean Square of Pitch Command
trs_theta_desired_tol	Tolerance for Desired Pitch Region
trs_theta_err_mean	Mean Pitch Error
trs_theta_err_rms	Root Mean Square of Pitch Error
trs_theta_nrmse	Normalized Root Mean Square of Pitch Error
trs_theta_pct_adequate	Cumulative Percentage in Adequate Pitch Region
trs_theta_pct_desired	Cumulative Percentage in Desired Pitch Region
trs_theta_tot_adequate	Cumulative Time in Adequate Pitch Region
trs_theta_tot_desired	Cumulative Time in Desired Pitch Region
trs_tot_adequate	Cumulative Time in Both Pitch and Roll Adequate Regions
trs_tot_desired	Cumulative Time in Both Pitch and Roll Desired Regions

4. **Calibration Flight Data**: Some of the data collected by Calspan during the calibration flight was included for model verification. These files are described in Table G3 below.

Table G3: Calibration Flight Data Files

File Name	Description
1adasrap.mat	Aileron Stick Rap Case 1A
1adesrap.mat	Elevator Stick Rap Case 1A
1desstep.mat	Elevator Stick Step Case 1
2desdblt.mat	Elevator Stick Doublet Case 2
3cdasrap.mat	Aileron Stick Rap Case 3C
3cdesrap.mat	Elevator Stick Rap Case 3C
adasstep.mat	Aileron Stick Step Case A
bdasstep.mat	Aileron Stick Step Case B

5. **Frequency Response Analysis Software**: This software was written by Capt. Mary Manning USAF TPS Technical Support Division. It is described in detail in Appendix E.

6. **Handling Qualities Toolbox**: This toolbox is a set of 23 MatLab ".M" files that automate the pilot models in Mil-STD-1797. It was used to determine the pilot model predictions described in the Test Results section of this report.

7. **Video Tape Records**: All of the tasks were recorded by direct video feed on to 2 hour, 8 mm video cassettes. These tapes were transferred to VHS and included as part of this data base. These tapes also provide an audio record of pilot ratings and comments.

APPENDIX H

COOPER-HARPER RATINGS AND PILOT COMMENTS

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COOPER-HARPER RATINGS AND PILOT COMMENTS

GENERAL

The three tables in this appendix present the Cooper-Harper ratings and pilot comments gathered during this evaluation. Table H1 summarizes the Cooper-Harper ratings and tracking task scoring variables by dynamics case for ground tracking runs. Table H2, starting on page 77, summarizes the Cooper-Harper ratings and tracking task scoring variables by dynamics cases for airborne evaluations. Table H3, starting on page 83, contains pilot comments for all ground tracking runs. This table is arranged by flight and record number so that the user can cross-reference these comments with the video tape record described in Appendix G. Table H4, starting on page 91, contains pilot comments for the airborne simulations. These comments are again arranged by session and event number for video cross-referencing.

Table H1: Cooper-Harper Ratings - Ground Simulations

Case	Task	Pilot	Iteration (Sortie #)	File Name	PIO	C-H Rating	% Desired	% Adequate
1	DISC	DG	1(1)	G1XD_G_1	1	2	77	91
1	SOS	DG	1(1)	G1XS_G_1	1	2	49	90
1	DISC	RS	2(3)	G1XD_S_3	2	3	80	92
1	SOS	RS	2(3)	G1XS_S_3	1	3	52	91
2	DISC	CE	1(2)	G2XD_E_2	2	4	66	79
2	SOS	CE	1(2)	G2XS_E_2	2	4	54	86
2	DISC	RS	2(3)	G2XD_S_3	2	2	74	88
2	SOS	RS	2(3)	G2XS_S_3	2	3	39	76
3	DISC	DG	1(1)	G3XD_G_1	2	3	75	92
3	SOS	DG	1(1)	G3XS_G_1	3	5	43	82
3	DISC	RS	2(6)	G3XD_S_6	1	2	75	95
3	SOS	RS	2(6)	G3XS_S_6	2	4	39	81
4	DISC	DG	1(1)	G4XD_G_1	3	4	63	91
4	SOS	DG	1(1)	G4XS_G_1	4	6	44	72
4	DISC	CE	2(5)	G4XD_S_5	1	4	64	84
4	SOS	CE	2(5)	G4XS_S_5	2	4 (5)	35	68
A	DISC	CE	1(2)	GXAD_E_2	1	1	71	84
A	SOS	CE	1(2)	GXAS_E_2	1	1	80	99
A	DISC	RS	2(3)	GXAD_S_3	1	4	77	85
A	SOS	RS	2(3)	GXAS_S_3	2	2	88	99
B	DISC	DG	1(4)	GXBD_G_4	1	2	75	90
B	SOS	DG	1(4)	GXBS_G_4	1	2	82	100
B	DISC	CE	2(5)	GXBD_E_5	1	2	68	85
B	SOS	CE	2(5)	GXBS_E_5	1	2	75	98
C	DISC	CE	1(5)	GXCD_E_5	1	4	66	80
C	SOS	CE	1(5)	GXCS_E_5	2	4	63	91
C	DISC	RS	2(6)	GXCD_S_6	3	5 (4)	64	82
C	SOS	RS	2(6)	GXCS_S_6	2	3	77	99
D	DISC	CE	1(2)	GXDD_E_2	3	5	40	72
D	SOS	CE	1(2)	GXDS_E_2	3	5	61	87

Table H1: Cooper-Harper Ratings - Ground Simulations (continued)

Case	Task	Pilot	Iteration (Sortie #)	File Name	PIO	C-H Rating	% Desired	% Adequate
D	DISC	DG	2(4)	GXDD_G_4	3	5 (4)	53	79
	SOS			GXDS_G_4	2	3	77	96
1A	DISC	DG	1(4)	G1AD_G_4	1	3	57	82
	SOS			G1AS_G_4	1	3 (4)	41	93
1B	DISC	CE	1(2)	G1BD_E_2	1	2	66	85
	SOS			G1BS_E_2	1	2	42	84
1C	DISC	DG	1(1)	G1CD_G_1	1	3	43	73
	SOS			G1CS_G_1	1	4	48	90
1D	DISC	RS	1(3)	G1DD_S_3	3	7	33	62
	SOS			G1DS_S_3	4	7	25	72
2A	DISC	RS	1(3)	G2AD_S_3	3	5 (4)	54	72
	SOS			G2AS_S_3	2	4	37	81
2B	DISC	DG	1(1)	G2BD_G_1	4	6	34	66
	SOS			G2BS_G_1	3	5	32	78
2C	DISC	CE	1(5)	G2CD_E_5	2	6	35	60
	SOS			G2CS_E_5	2	6	21	72
2D	DISC	DG	1(4)	G2CD_G_4	4	7	21	50
	SOS			G2CS_G_4	4	6	19	67
3A	DISC	DG	1(1)	G3AD_G_1	1	3	48	79
	SOS			G3AS_G_1	1	2	41	82
3B	DISC	RS	1(3)	G3BD_S_3	3	4	51	77
	SOS			G3BS_S_3	2	4	31	77
3C	DISC	CE	1(2)	G3CD_E_2	1	6	35	65
	SOS			G3CS_E_2	3	6	22	72
3D	DISC	RS	1(6)	G3DD_S_6	3	6	19	56
	SOS			G3DS_S_6	3	7	7	47
4A	DISC	CE	1(2)	G4AD_E_2	1	3	43	72
	SOS			G4AS_E_2	2	4 (5)	27	67
4B	DISC	RS	1(3)	G4BD_S_3	3	5	32	66
	SOS			G4BS_S_3	3	4 (5)	27	71

Table H1: Cooper-Harper Ratings - Ground Simulations (continued)

Case	Task	Pilot	Iteration (Sortie #)	File Name	PIO	C-H Rating	% Desired	% Adequate
4C	DISC	CE	1(5)	G4CD_E_5	1	5	32	63
	SOS			G4CS_E_5	2	5	23	64
4D	DISC	DG	1(1)	G4DD_G_1	2	7	21	43
	SOS			G4DS_G_1	2	5	21	67

Table H2: Cooper-Harper Ratings - Airborne Evaluations

Case	Task	Pilot	Iteration (Sortie #)	File Name	PIO	C-H Rating	% Desired	% Adequate
1	DISC	DG	1(1)	F1XD_G_1	1	3	83	92
	SOS			F1XS_G_1	1	2	67	98
	REJ			F1XR_G_1	1	2	90	100
1	DISC	RS	2(2)	F1XD_S_2	2	3	82	94
	SOS			F1XS_S_2	2	3	68	97
	REJ			F1XR_S_2	1	2	88	99
1	DISC	DG	3(5)	F1XD_G_5	1	1	81	97
	SOS			F1XS_G_5	1	2	69	96
	REJ			F1XR_G_5	1	2	91	99
2	DISC	CE	1(1)	F2XD_E_1	1	1	80	92
	SOS			F2XS_E_1	1	1	53	93
	REJ			F2XR_E_1	1	1	82	98
2	DISC	RS	2(2)	F2XD_S_2	1	2	72	89
	SOS			F2XS_S_2	1	2	63	98
	REJ			F2XR_S_2	1	3	75	96
2	DISC	DG	3(5)	F2XD_G_5	1	2	80	96
	SOS			F2XS_G_5	1	2	70	97
	REJ			F2XR_G_5	1	2	93	99
3	DISC	DG	1(1)	F3XD_G_1	2	3	79	91
	SOS			F3XS_G_1	4	5	45	86
	REJ			F3XR_G_1	4	4	73	95
3	DISC	RS	2(2)	F3XD_S_2	3	5	77	93
	SOS			F3XS_S_2	4	5	48	97
	REJ			F3XR_S_2	4	5	65	96
3	DISC	DG	3(5)	F3XD_G_5	1	3	75	91
	SOS			F3XS_G_5	2	3	62	98
	REJ			F3XR_G_5	2	3	86	99
4	DISC	DG	1(1)	F4XD_G_1	4	4	73	92
	SOS			F4XS_G_1	4	4	47	89
	REJ			F4XR_G_1	4	4	73	95

Table H2: Cooper-Harper Ratings - Airborne Evaluations (continued)

Case	Task	Pilot	Iteration (Sortie #)	File Name	PIO	C-H Rating	% Desired	% Adequate
4	DISC	CE	2(2)	F4XD_E_2	2	4	67	88
	SOS			F4XS_E_2	2	4	48	80
	REJ			F4XR_E_2	3	5	69	94
4	DISC	CE	3(5)	F4XD_E_5	2	4	69	91
	SOS			F4XS_E_5	3	5	41	76
	REJ			FRXR_E_5	4	4	73	95
A	DISC	DG	1(1)	FXAD_G_1	1	2	77	86
	SOS			FXAS_G_1	1	1	91	100
	REJ			FXAR_G_1	1	1	100	100
A	DISC	CE	2(2)	FXAD_E_2	1	3	77	87
	SOS			FXAS_E_2	1	3	86	99
	REJ			FXAR_E_2	1	2	99	99
A	DISC	CE	3(5)	FXAD_E_5	1	1	74	84
	SOS			FXAS_E_5	1	1	95	99
	REJ			FXAR_E_5	1	1	99	99
B	DISC	CE	1(1)	FXBD_E_1	1	3	66	84
	SOS			FXBS_E_1	1	2	86	99
	REJ			FXBR_E_1	1	1	96	100
B	DISC	CE	2(2)	FXBD_E_2	2	4	62	86
	SOS			FXBS_E_2	2	4	82	99
	REJ			FXBR_E_2	1	2	99	99
B	DISC	DG	3(5)	FXBD_G_5	1	2	81	91
	SOS			FXBS_G_5	1	2	90	99
	REJ			FXBR_G_5	1	2	99	99
C	DISC	CE	1(1)	FXCD_E_1	3	5	63	79
	SOS			FXCS_E_1	2	4	74	100
	REJ			FXCR_E_1	2	3	99	100
C	DISC	CE	2(2)	FXCD_E_2	3	5	65	77
	SOS			FXCS_E_2	2	4	79	99
	REJ			FXCR_E_2	2	3	95	99

Table H2: Cooper-Harper Ratings - Airborne Evaluations (continued)

Case	Task	Pilot	Iteration (Sortie #)	File Name	PIO	C-H Rating	% Desired	% Adequate
C	DISC	DG	3(5)	FXCD_G_5	2	4	68	83
	SOS			FXCS_G_5	2	4	79	99
	REJ			FXCR_G_5	2	3	95	99
D	DISC	CE	1(1)	FXDD_E_1	4	6	61	74
	SOS			FXDS_E_1	4	6	62	93
	REJ			FXDR_E_1	2	4	75	95
D	DISC	RS	2(2)	FXDD_S_2	4	7	47	74
	SOS			FXDS_S_2	4	7	71	98
	REJ			FXDR_S_2	4	8	74	93
D	DISC	DG	3(5)	FXDD_G_5	4	5	62	82
	SOS			FXDS_G_5	3	4	77	98
	REJ			FXDR_G_5	3	4	88	99
1A	DISC	RS	1(2)	F1AD_S_2	3	4	57	82
	SOS			F1AS_S_2	2	4	60	95
	REJ			F1AR_S_2	2	3	94	99
1A	DISC	DG	2(3)	F1AD_G_3	1	3	58	80
	SOS			F1AS_G_3	2	3	53	98
	REJ			F1AR_G_3	1	3	87	99
1B	DISC	CE	1(2)	F1BD_E_2	1	3	54	82
	SOS			F1BS_E_2	1	3	46	90
	REJ			F1BR_E_2	1	2	89	99
1B	DISC	RS	2(3)	F1BD_S_3	3	5	59	85
	SOS			F1BS_S_3	3	5	50	99
	REJ			F1BR_S_3	2	4	88	99.9
1C	DISC	RS	1(3)	F1CD_S_3	3	5	49	81
	SOS			F1CS_S_3	4	5	37	96
	REJ			F1CR_S_3	2	4	93	99
1C	DISC	CE	2(4)	F1CD_E_4	2	6	48	73
	SOS			F1CS_E_4	2	5	47	88
	REJ			F1CR_E_4	2	4	89	100

Table H2: Cooper-Harper Ratings - Airborne Evaluations (continued)

Case	Task	Pilot	Iteration (Sortie #)	File Name	PIO	C-H Rating	% Desired	% Adequate
1D	DISC	DG	1(3)	F1DD_G_3	4	6	45	76
	SOS			F1DS_G_3	4	5	45	90
	REJ			F1DR_G_3	4	6	53	94
1D	DISC	DG	2(4)	F1DD_G_4	1	4	51	82
	SOS			F1DS_G_4	2	4	46	90
	REJ			F1DR_G_4	2	3	78	94
2A	DISC	RS	1(3)	F2AD_S_3	2	2	61	80
	SOS			F2AS_S_3	1	3	57	98
	REJ			F2AR_S_3	1	2	85	99
2A	DISC	CE	2(4)	F2AD_E_3	2	3	56	80
	SOS			F2AS_E_3	2	3	55	93
	REJ			F2AR_E_3	1	2	92	100
2B	DISC	RS	1(3)	F2BD_S_3	2	3	61	83
	SOS			F2BS_S_3	2	3	51	97
	REJ			F2BR_S_3	1	3	89	99
2B	DISC	CE	2(5)	F2AD_E_5	2	4	51	79
	SOS			F2AS_E_5	2	4	55	92
	REJ			F2A_E_5	2	5	88	99
2C	DISC	RS	1(3)	F2CD_S_3	3	5	54	83
	SOS			F2CS_S_3	3	5	45	98
	REJ			F2CR_S_3	2	4	92	99
2C	DISC	CE	2(4)	F2CD_E_4	3	5	44	74
	SOS			F2CS_E_4	3	6	42	84
	REJ			F2CR_E_4	3	5	87	99
2D	DISC	DG	1(3)	F2CD_G_3	4	5	46	78
	SOS			F2CS_G_3	3	4	46	91
	REJ			F2CR_G_3	2	4	67	98
2D	DISC	CE	2(5)	F2CD_E_5	5	7	38	68
	SOS			F2CS_E_5	4	6	42	87
	REJ			F2CR_E_5	4	7	65	97

Table H2: Cooper-Harper Ratings - Airborne Evaluations (continued)

Case	Task	Pilot	Iteration (Sortie #)	File Name	PIO	C-H Rating	% Desired	% Adequate
3A	DISC	CE	1(4)	F3AD_E_4	1	4	45	77
	SOS			F3AS_E_4	2	4	45	83
	REJ			F3AR_E_4	2	4	74	98
3A	DISC	CE	2(5)	F3AD_E_5	2	4	49	72
	SOS			F3AS_E_5	2	4	51	89
	REJ			F3AR_E_5	2	3	85	99
3B	DISC	DG	1(3)	F3AD_G_3	1	2	58	92
	SOS			F3AS_G_3	2	3	53	91
	REJ			F3AR_G_3	2	3	82	98
3B	DISC	DG	2(4)	F3BD_G_4	2	3	63	82
	SOS			F3BS_G_4	3	4	46	87
	REJ			F3BR_G_4	2	3	79	99
3C	DISC	RS	1(3)	F3CD_S_3	4	5	44	80
	SOS			F3CS_S_3	4	6	32	88
	REJ			F3CR_S_3	2	5	81	99
3C	DISC	CE	2(4)	F3CD_E_4	3	6	34	71
	SOS			F3CS_E_4	4	6	39	81
	REJ			F3CR_E_4	3	5	71	97
3D	DISC	DG	1(4)	F3DD_G_4	4	6	43	78
	SOS			F3DS_G_4	4	5	39	85
	REJ			F3DR_G_4	4	5	70	97
4A	DISC	DG	1(4)	F4AD_G_4	2	4	53	81
	SOS			F4AS_G_4	3	5	46	91
	REJ			F4AR_G_4	3	4	78	98
4A	DISC	DG	2(5)	F4AD_G_5	3	4	57	82
	SOS			F4AS_G_5	3	4	44	89
	REJ			F4AR_G_5	2	3	77	98
4B	DISC	CE	1(4)	F4BD_E_4	3	5	49	84
	SOS			F4BS_E_4	4	6	33	75
	REJ			F4BR_E_4	4	6	63	96

Table H2: Cooper-Harper Ratings - Airborne Evaluations (continued)

Case	Task	Pilot	Iteration (Sortie #)	File Name	PIO	C-H Rating	% Desired	% Adequate
4B	DISC	CE	2(5)	F4BD_E_5	3	5	39	74
	SOS			F4BS_E_5	3	5	49	90
	REJ			F4BR_E_5	3	5	72	92
4C	DISC	DG	1(4)	F4CD_G_4	4	6	42	71
	SOS			F4CS_G_4	4	5	43	85
	REJ			F4CR_G_4	4	5	95	95
4D	DISC	DG	1(4)	F4DD_G_4	3	5	47	76
	SOS			F4DS_G_4	4	5	34	82
	REJ			F4DR_G_4	3	4	92	92
4D	DISC	CE	2(5)	F4DD_E_5	4	7	29	65
	SOS			F4DS_E_5	4	6	33	82
	REJ			F4DR_E_5	4	6	95	95

Table H3: Pilot Comments During Ground Evaluation

Have Pilot			Ground 1 Pilot: Darcy Granley
Record	File Name	C-H Rating	Qualitative Comments
1	G1XD_G_1	2	No tendency to PIO. Good response in the pitch axis. No tendency to overshoot. Pilot compensation was not a factor. Didn't have to be overly aggressive.
2	G1XS_G_1	2	Have to concentrate to keep the horizon line straight. Find myself concentrating on the pitch axis and neglecting the roll axis. Good response in the pitch axis. I didn't have to be overly aggressive.
3	G3XD_G_1	3	A little bit sensitive in pitch. Slight PIO at large discrete changes, but not uncontrollable. Aircraft characteristics were fair. Aircraft response was good, predictable. Almost felt like the same task as before, but with a slight tendency to PIO.
4	G3XS_G_1	5	Large inputs required. A little PIOing. A little sensitive in the pitch axis. Lead input required to get the aircraft where I wanted it to go. I had to be aggressive.
5	G4XD_G_1	4	I can see a PIO tendency. Aircraft responds well, but I need to lead the end point. When the gain goes up the aircraft tends to PIO. When the piper was on the marker my aggressiveness was low.
6	G4XS_G_1	6	Large inputs required. Tendency to PIO. Just can't let off for a second. Have to come out of the loop to avoid PIO tendency.
7	G2BD_G_1	6	Yikes! Roll axis is a big problem. Real tendency to PIO in roll, but it never was divergent. I find myself really anticipating. Had to be very aggressive throughout the task. Large lead inputs were required to get the aircraft moving and also have it stop were I wanted it.
8	G2BS_G_1	5	I need to put some heavy inputs in. The aircraft is fairly responsive in pitch. It was more difficult to control the roll as compared to pitch. Had to be fairly aggressive throughout the task. Tended to overshoot a little bit in roll.
9	G4DD_G_1	7	I tried to be aggressive, but I had to come out of the loop a little bit. Felt like the aircraft had a lag. I needed large inputs to get the aircraft going. It felt like I was one step behind the aircraft the whole time.
10	G4DS_G_1	5	Pitch is not a problem. I find myself rolling back and forth. Can't seem to reduce my gain here at all. I could never catch up with the roll axis.
11	G3AD_G_1	3	I need good motion on the stick to get the aircraft going. No requirement to come out of the loop. No PIO tendency.
12	G3AS_G_1	2	No tendency to PIO. Good solid movements on stick. A little heavy but not objectionable. Aircraft characteristics were good. I didn't have to be overly aggressive. The aircraft did what you commanded it to do.
13	G1CD_G_1	3(4)	I'm having to be fairly aggressive. Good in the pitch. Roll is fairly well too. No tendency to PIO. A couple of times in the roll axis I thought I was over controlling. Pitch axis was quite nice. In the roll axis I had to be a little more aggressive but it didn't effect the handling qualities.

Table H3: Pilot Comments During Ground Evaluation (continued)

Have Pilot		Ground 1	Pilot: Darcy Granley
14	G1CS_G_1	4	Hard to keep the airplane lined up in the roll axis, and it was a bit annoying. The aircraft responded well in pitch. I always had a slight oscillation in roll, and because of that the work load went up.

Table H3: Pilot Comments During Ground Evaluation (continued)

Have Pilot		Ground 2	Pilot: Craig Edkins
Record	File Name	C-H Rating	Qualitative Comments
1	G2XD_E_2	4	Initial response was quick in pitch, but was found to be oscillatory. I had to back out due to oscillations.
2	G2XS_E_2	4	Satisfactory. Initial response was quick. Tendency to overshoot. Had to use a lot of lead for stopping it on gross acquisition.
3	GXDD_E_2	5	Slow initial response. Oscillatory. Tendency to overshoot. Couldn't be aggressive. I find myself backing out of the loop some. Big initial input to get the aircraft going. Half way to the command bar, I would pull out my input. The aircraft wasn't predictable.
4	GXDS_E_2	5	Sluggish initially. Tendency to overshoot. Big input to get the aircraft going...pull input out early to stop aircraft where I want it to stop. Lead input required. Backed out of the loop a little bit.
5	G1BD_E_2	2	Quick. Final response was fine. No tendency to overshoot or oscillate. No pilot compensation was necessary.
6	G1BS_E_2	2	Quick. Predictable. I could be aggressive. I had to put in a little more force in the pitch as compared to roll, but it wasn't objectionable.
7	G3CD_E_2	6	Very objectionable, but tolerable deficiencies. Slow. Had to put in big inputs. Applied a lot of lead to counter big inputs. I could be aggressive, but a whole lot of lead was required.
8	G3CS_E_2	6	Sluggish. A lot of lead required to roll out. Not very predictable. Got into an oscillation when I got very aggressive. I had to back out of the loop at certain points.
9	G4AD_E_2	3	Roll was nice. Pitch was adequate. Predictable in both axes. Could be aggressive in both axes without trouble. Quite a bit of aggressiveness in the pitch axis was required as compared to the roll axis.
10	G4AS_E_2	4(5)	Roll was fine. Seemed to be O.K. in roll, but out of there in pitch. I spend a lot of time aligned in roll but not pitch. Sluggish in pitch. Aggressive throughout resulted in undesirable motion in pitch.
11	GXAD_E_2	1	Quick. Predictable. Pretty aggressive during task. Simple to fly.
12	GXAS_E_2	1	Quick. Predictable. Fairly aggressive. Pilot compensation was not a factor.

Table H3: Pilot Comments During Ground Evaluation (continued)

Have Pilot		Ground 3	Pilot: Russ Sellers
Record	File Name	C-H Rating	Qualitative Comments
8	G4BS_S_3	4(5)	I can be pretty aggressive in pitch. Occasional overshoots in both pitch and roll. Need to back out of the loop to reacquire...especially in roll.
9	G2AD_S_3	5(4)	Couple of overshoots in pitch. Sluggish in roll. Relatively quick in pitch. Tendency to overshoot in pitch, but slow in roll. Tended to back out of the loop in pitch. No large tendency to overshoot.
10	G2AD_S_3	4	A little tendency to overshoot in pitch. Roll is slow. Find it difficult to track in roll. Hard to back out of the loop in pitch and still be aggressive in roll. Really yanking on it to make it move in roll. I have to be pretty aggressive in roll. I have to be aware of the tendency to overshoot in pitch.
11	G1XD_S_3	3	Crisp response in the beginning. Couple of overshoots, but pretty small. A little sluggish in pitch when I have tc make big motions. Some minimal compensation. Being initially more aggressive and then backing out a little bit.
12	G1XS_S_3	3	A little bit slow in pitch. Maybe one overshoot in pitch. Had to lead just a little bit. Compensated by pulling a little harder. The more aggressive I got the better I could track and reduce the error. Had to lead a little bit and stay in the loop.
13	G1DD_S_3	7	In roll this is not fun. Have to back out of the loop to keep from overshooting. Pitch isn't too bad. Roll is sluggish. No tendency to oscillate in roll. Predictable. Had to come out of the loop to prevent overshoots in roll. Large deflection roll input to get the aircraft moving, then came out right away to prevent overshoots.
14	G1DS_S_3	7	Almost oscillatory in roll. Sluggish in roll. No fun at all. Almost feels a little sluggish in pitch. Oscillatory, couldn't come out of the loop. Initial response was sluggish in roll and tended to overshoot and even oscillate. Initial pitch response was a little slow and had a slight tendency to overshoot. Couldn't be as aggressive as I wanted to be. Got in the loop to get within criteria and would then slightly come out of the loop.

Table H3: Pilot Comments During Ground Evaluation (continued)

Have Pilot		Ground 4	Pilot: Darcy Granley
Record	File Name	C-H Rating	Qualitative Comments
1	GXBD_G_4	2	Jerky. I can relax my gain when tracking. I didn't have to be aggressive. Work load was fine. I liked the way it flew.
2	GXBS_G_4	2	Initial input was good. No tendency to overshoot. Work load isn't too high. I can relax and reduce my work load.
3	G1AD_G_4	3	Pretty good response in pitch and roll. Little more sensitive in pitch, but it's a little slow. Need a lead input in pitch, but it's not objectionable.
4	G1AS_G_4	3(4)	Just a little lead compensation in pitch. Roll seems to be O.K. Have to be fairly aggressive. Can't really take yourself out of the loop. Initial response was a little sluggish.
5	G2DD_G_4	7	Tendency for a little PIOing. Not predictable. Good initial response. Pitch is not a problem. Roll is more of the problem. When you become to aggressive you need to come out of the loop due to the PIOing in roll.
6	G2DS_G_4	6	Overshooting in pitch and roll. Pilot work load is high all the way through. Initial response is good but not predictable. Need to be aggressive to get the aircraft going, but then had to come out of the loop.
7	GXDD_G_4	5(4)	Tendency to overshoot. Have to come out of the loop a little bit. Not very predictable. Initial response was a little slow. Had to be aggressive to get the aircraft going. Very annoying.
8	GXDS_G_4	3	A slight tendency to overshoot when you get a discrete movement. Pilot work load is tolerable. Gain goes up and down. A little annoying. Initial response was good. Just a little oscillation, but it wasn't objectionable. Fairly reasonable flying characteristics. Aircraft pretty much did what I wanted it to do.

Table H3: Pilot Comments During Ground Evaluation (continued)

Have Pilot		Ground 5	Pilot: Craig Edkins
Record	File Name	C-H Rating	Qualitative Comments
1	G4XD_E_5	4	Slow. Predictable. Didn't have to back out. Had to put in large inputs for discrete acquisition.
2	G4XS_E_5	4(5)	Noticing some undesirable motion. Slow. Tend to overshoot. Well damped but unpredictable. Required lead compensation.
3	G2CD_E_5	6	A little oscillation in pitch. Quick in pitch. The roll was sluggish/slow and unpredictable. Had to back out in pitch to avoid oscillation. Need a little lead compensation.
4	G2CS_E_5	6	Pitch again is oscillatory. Roll is sluggish. Not a good combination. Initial response in pitch was quick whereas roll was slow. Neither are predictable. Had to back out in pitch. I had more control in roll. Lacked control harmony...easy on the pitch, hard on the roll.
5	GXBD_E_5	2	Quick in roll. Not too bad. Predictable. I could be fairly aggressive. It was good.
6	GXBS_E_5	2	Quick. Predictable. Again I could be fairly aggressive. Comfortable. Stayed in the loop.
7	G4CD_E_5	5	I don't like the roll. Really working hard. I don't think pitch is bad though. Both axes were slow. Final response in roll wasn't predictable. I had to use aileron doublets to control my desired roll. Had to back out a little bit.
8	G4CS_E_5	5	Initial response was sluggish. Not predictable. A slight bobble was noticed and was found to be undesirable. Used a little lead input.
9	GXCD_E_5	4	A little slow. Doesn't really roll like a fighter. Minor but annoying deficiencies. Concentrating real hard. Fairly predictable.
10	GXCS_E_5	4	A little undesirable motion. Like fine tracking. Need to back out a little. Not real bad just kind of annoying. Not slow, but not predictable. Had to come out of the loop slightly. A little oscillatory motion, but it did not compromise the task.

Table H3: Pilot Comments During Ground Evaluation (continued)

Have Pilot		Ground 6	Pilot: Russ Sellers
Record	File Name	C-H Rating	Comments: Russ II
1	GXCD_S_6	5(4)	Little sluggish in roll. Causing me to overshoot a couple of times. Once I've acquired in roll it's easy to track. Initial response was slow. Tendency to overshoot. Level of aggressiveness caused one to overshoot during acquisition. Had to back out of the loop a little bit.
2	GXCS_S_6	3	Overshoots in roll. Easy to maintain track once I've acquired. A little compensation required. Tend to back out of the loop when I was overshooting. Slow initial response. Some tendency to overshoot.
3	G3DD_S_6	6	A lot of tendency to overshoot in roll. A few overshoots in pitch. Roll is real nasty to deal with here. Very sluggish in pitch. A few overshoots in pitch. Extensive compensation even for adequate performance. Pitch was quick. Roll was slow. Had to come out of the loop a little bit in both pitch and roll...mostly roll. Roll was definitely worse. Control harmony problem.
4	G3DS_S_6	7	Couple of overshoots in pitch. Very difficult to maintain track in roll. Feels like I'm leading with some opposite roll. Roll was slow and sluggish. Many overshoots in roll. Had to come out of the loop...degraded my ability to track. Disparity between the response in pitch and roll effected my tracking.
5	G3XD_S_6	2	Initial acquisition in pitch is slower. No tendency to overshoot so far. Pretty easy task. Was compensating a little. Response was a little slower than I like. Final response was predictable. Came out of the loop a little when I noticed small overshoots. Use a little less gain during acquisition.
6	G3XS_S_6	4	Slow initial response. Pushing pretty hard. Initial response in pitch was more sluggish than I like. Required moderate compensation by being aggressive. Slight tendency to overshoot. Being more aggressive with my initial input to make up for the slow response.

Table H3: Pilot Comments During Ground Evaluation (continued)

Have Pilot		Ground 7	Pilot: Russ Sellers
Record	File Name	C-H Rating	Qualitative Comments
15	G2XD_S_7	2	Easy to track in pitch. Not a lot of compensation involved. Easy to acquire. No compensation required. Quick. Tend to overshoot once or twice. Slightly back out of the loop when I acquired it.
16	G2XS_S_7	3	Easy to acquire. Couple of overshoots. Slightly sensitive in pitch. Quick...maybe too quick. Some tendency to overshoot. Could be pretty aggressive all the way through the task.
17	GXAD_S_7	3	A little slow in roll. Easy to acquire. No tendency to overshoot. Minimal compensation. Need a lot of input initially to get the aircraft rolling. Predictable. Being more aggressive did not effect my tracking capability.
18	GXAS_S_7	2	One overshoot in roll. Slow response. Have to roll pretty hard. Pretty easy to reacquire. No undesirable motions. Compensation was not a factor to maintain track...only during reacquisition. Increase aggressiveness to compensate for sluggishness. Predictable final response.
19	G3BD_S_7	4	Pretty tricky in pitch. Easy to maintain desired in pitch. Roll is a little sluggish. Pitch may be a little sensitive. Couple of overshoots in pitch. Pitch was quick and jerky. Overshoots two or three times. Had to back out a little. Had to be aggressive in roll due to the sluggishness.
20	G3BS_S_7	4	Roll seems a little siuggish. Pitch seems O.K. Having a hard time trying to match roll rate. Tendency to overshoot in roll a couple of times. Slow roll response. Had to use big inputs to get it going. Aggressive tracking was possible in roll...not so much in pitch. Fairly predictable in pitch. Reacquiring was worse in roll.

Table H4: Pilot Comments During Airborne Evaluation

Have Pilot	Sortie 1	Pilot: Craig Edkins	Flight #: 0398
Record	File Name	C-H Rating	Qualitative Comments
7	FXDD_E_1	6	I really need to be easy and smooth with my inputs. A lot of lead input was required. I have to back out of the loop to minimize error. There's a definite PIO tendency.
8	FXDS_E_1	6	I had to back out of the loop and it required lots of lead.
9	FXDR_E_1	4	Control inputs were like doublets. Flying with my fingers, not my fists. Backed out of the loop.
10	F2XD_E_1	1	The initial response was quick and predictable. No compensation technique was required.
11	F2XS_E_1	1	On the ground I push as hard as I pull, but in the air my body tells me to back off.
12	F2XR_E_1	1	Quick and predictable. I could be fairly aggressive.
13	FXBD_E_1	3	I can be fairly aggressive. May lack a little predictability. Initial response is O.K. There's no tendency to overshoot.
14	FXBS_E_1	2	Initial response is O.K. Definite learning curve...I have to put in a big input and take it out right away. Flying a lot of lead.
15	FXBR_E_1	1	Initial response was quick. I could be as aggressive as I needed to be to accomplish the task.
16	FXCD_E_1	5	Slow/sluggish initial response. A lot of lead was required. A lot of oscillations. Put a big input in and then pull it out right away. A lot of anticipation is required.
17	FXCS_E_1	4	If I get to aggressive, I tend to get more oscillations. Aircraft response is sluggish and a little unpredictable.
18	FXCR_E_1	3	Backing out of the loop helps. Fighting it causes excess oscillations. Response seemed a bit sluggish.

Table H4: Pilot Comments During Airborne Evaluation (continued)

Have Pilot	Sortie 1	Pilot: Darcy Granley	Flight #: 0398
Record	**File Name**	**C-H Rating**	**Qualitative Comments**
19	F3XD_G_1	3	Good initial response. Quick. Slight tendency to PIO. Slight overshoot tendency. I did not have to be overly aggressive.
20	F3XS_G_1	5	More tendency to be oscillatory. Need to come out of the loop. More tendency to PIO. Very unpredictable in the final response. Had to be aggressive in the task. I could never relax.
21	F3XR_G_1	4	Need a large lead input to get desired response. Initial response is not too bad. Still have a slight tendency to PIO. I had to come out of the loop to prevent PIO tendency.
22	F4XD_G_1	4	Good initial response. Very quick. Have to come out of the loop to reduce PIO tendency. Final response is not very predictable.
23	F4XS_G_1	5	Can see PIO tendency here. Can't be too aggressive. Very light on the controls, almost have to come off of it when you get on the target. High pilot workload. Quick initial response. Can't have too large of an input to avoid a PIO tendency.
24	F4XR_G_1	4	Initial response was good. Have to come out of the loop to avoid PIO tendency
25	FXAD_G_1	2	Fairly good initial response. No tendency to PIO. Fairly predictable. Wasn't too quick or too slow. No compensation required.
26	FXAS_G_1	1	No tendencies to overshoot. Pilot gains go up and down, but the workload is satisfactory. Final response is very predictable. In general I liked the way the aircraft handled.
27	FXAR_G_1	1	Not difficult at all to keep wings level. Good initial response. Fairly simple task. I'm not working hard at all.
28	F1XD_G_1	2	Good initial response - very quick. Almost have to come out of the loop in order not to be too jerky. Predictable and no tendency to PIO. Didn't have to be too aggressive with the initial response.
29	F1XS_G_1	2	Fairly predictable - no tendency to PIO. Basically does what you want it to do. Definitely a good initial response. No real compensation techniques used.
30	F1XR_G_1	2	Not an overly difficult task. Good initial response. No real compensation required.

Table H4: Pilot Comments During Airborne Evaluation (continued)

Have Pilot Sortie 2 Pilot: Russ Sellers Flight #: 0399			
Record	File Name	C-H Rating	Qualitative Comments
1	F2XD_S_2	2	No PIO tendencies. Tracking is easy. Acquisition is easy. Initial response was quick. Final response predictable. More aggressiveness resulted in PIO tendency...had to back out slightly.
2	F2XS_S_2	2	No tendency to PIO. Tracking requires pretty high gain. Compensation wasn't a factor. Level of aggressiveness increased the number of overshoots. Backed out just a little bit.
3	F2XR_S_2	3	More tendency to overshoot. Initial response is a little slow. Tracking is easy. Acquisition is more difficult. Had to be careful with the level of aggressiveness to avoid overshoots.
4	F3XD_S_2	5	Tendency to oscillate. Initial acquisition gives several overshoots and oscillation. Tracking when on target is easy. Can sense time. Overshoots did compensate task. During acquisition I had to come out of the loop to keep from oscillating.
5	F3XS_S_2	5	Can track fairly aggressively. Moderately objectionable. Slow initial response...interpret as time delay. Level of aggressiveness effects acquisition more than tracking.
6	F3XR_S_2	5/4	A little tendency to oscillate. Can't tell if I was oscillating or having a couple of overshoots. I really worked to come in and out of the loop. I had to back out of the loop to reduce oscillations.
7	F1XD_S_2	3	No oscillations in track. One or two overshoots in acquisition. Slow initial response. Level of aggressiveness affected the acquisition but not the tracking portion of the task.
8	F1XS_S_2	3	Backed out of the loop to prevent oscillation tendencies.
9	F1XR_S_2	2	Not a lot of difficulty tracking at all. A little slow in the initial response. Final response was predictable. Level of aggressiveness did not effect the task.
10	FXDD_S_2	7	Not nice in roll at all. Have to come out of the loop to stop oscillations. Practically have to let go of the stick. Initial response was slow. Tendency to overshoot. Had to come off of the stick after initial inputs.
11	FXDS_S_2	7	Oscillating within desired criteria. Practically flying this open loop. Initial response was slow. Tendency to overshoot. I would make an input and practically come free of the stick.
12	FXDR_S_2	8	Can't come out of the loop. Have to stay in the loop to maintain wings level which then wants to oscillate. I wouldn't want to fly this. Almost on the verge of diverging. Had to come out of the loop to keep from oscillating.

Table H4: Pilot Comments During Airborne Evaluation (continued)

Have Pilot	Sortie 2	Pilot: Russ Sellers	Flight #: 0399
Record	**File Name**	**C-H Rating**	**Qualitative Comments**
13	F1AD_S_2	4	Can track as tightly as I want. A couple of overshoots in roll and pitch. Initial response was quick in pitch and slow in roll. Had to back out of the loop to prevent overshoots.
14	F1AS_S_2	4	Roll doesn't seem as bad here as on the discrete task. A little slow in roll. Had to come out of the loop in pitch to prevent oscillations.
15	F1AR_S_2	3	Not much of a tendency to oscillate. Occasional one or two overshoots in pitch and roll. Quick in roll. Fairly predictable. Felt nice. In the pitch axis I had to come out of the loop to reduce overshoots.

Table H4: Pilot Comments During Airborne Evaluation (continued)

Have Pilot	Sortie 2	Pilot: Craig Edkins	Flight #: 0399
Record	**File Name**	**C-H Rating**	**Qualitative Comments**
16	F4XD_E_2	4	Tendency to overshoot. Can't be aggressive like I would like to be. Flying is very sensitive and I must be easy with it. Quick. Less than predictable. I came out of the loop quite a bit.
17	F4XS_E_2	4	Have to coax it to get it where I want to be. Seems to be oscillatory especially when I try to be aggressive. Quick. Less than predictable. Tend to overshoot. Couldn't be as aggressive as I wanted to be.
18	F4XR_E_2	5	Still a little oscillatory. The more aggressive I become the more oscillatory it becomes. Quick. Less than predictable. Didn't come out of the loop. I just couldn't be aggressive.
19	FXAD_E_2	3	Initial response is quick and predictable. Maybe not as quick as I like it to be. Nice and predictable, but I'd like it to be faster. Could be very aggressive and stay in the loop. No special techniques required.
20	FXAS_E_2	3	Fine tracking is fairly simple. I can be fairly aggressive. No oscillations at all. Response was moderate and predictable. Minimal compensation required.
21	FXAR_E_2	2/1	Easy to damp out disturbances. Tracking to a finer degree. Easily controllable. I can be fairly aggressive to damp it out. Compensation wasn't a factor.
22	FXBD_E_2	4	Tendency to overshoot a little bit. Can be fairly aggressive. Takes some anticipation to roll out where I want to be. A little less than predictable. Could be fairly aggressive as long as I led my roll out.
23	FXBS_E_2	4	Doesn't excite problems. Fine tracking not a problem. Slight oscillatory tendency. Lack of predictability. Quick. Anticipation required to keep from generating undesirable motions.
24	FXBR_E_2	2	Can be fairly aggressive with it, but there is anticipation going on. Controlling it with a series of doublets. Had to back out of the loop a little bit to maximize performance.
25	FXCD_E_2	5	A lot of delay in roll. I can almost see it. Trying to roll out early in gros acquisition which would cause oscillations. I'd like to see it roll quicker. Couldn't be aggressive in fine tracking. I used a lot of anticipation to time gross acquisitions.
26	FXCS_E_2	4	I get behind when I try to be smooth. Can't be real aggressive in fine tracking. Slight delay. I'm being less than aggressive. Had to be gentle in the fine tracking.

Table H4: Pilot Comments During Airborne Evaluation (continued)

Have Pilot	Sortie 2	Pilot: Craig Edkins	Flight #: 0399
Record	**File Name**	**C-H Rating**	**Qualitative Comments**
27	FXCR_E_2	3	Starting to fight myself a little. Seems a little sluggish at times. Taking bigger inputs than what I would deem necessary. Fairly predictable. No compensation required.
28	F1BD_E_2	3	I like the roll. I'm fighting the pitch a little bit. I can be fairly aggressive in roll and kind of easy in pitch. Didn't notice any undesirable motion. I backed out of in pitch. Tend to overshoot in roll. Compensated by backing out of the loop a little bit.
29	F1BS_E_2	3	The pitch axis is really quick. Tend to overshoot in roll. Seems to be sensitive in pitch. Pitch seems a little abrupt to me. Most of the compensation is going on in the roll.
30	F1BR_E_2	2	Not noticing much error in pitch. Can't just max it out like in the single axis case. Aircraft response is fairly predictable. Fighting all axis a little bit.

Table H4: Pilot Comments During Airborne Evaluation (continued)

Have Pilot	Sortie 3	Pilot: Russ Sellers	Flight #: 0400
Record	**File Name**	**C-H Rating**	**Qualitative Comments**
1	F1CD_S_3	5	A few overshoots in roll. Can track real aggressively. Sluggish in roll and a little in pitch. Initial response is slow in pitch and roll. Overshoots in roll. Had to back out in roll to prevent overshoots.
2	F1CS_S_3	5	A little bit oscillatory in pitch and roll. Need to keep a lighter grip on the stick. Have to come out of the loop a little bit. Few overshoots in roll. The more aggressive I get the more oscillations I see. Tendency to overshoot in roll. Compensate by flying a little more open loop.
3	F1CR_S_3	4	A tendency to oscillate in roll. Keep a fairly light grip during the task. Fight tendency to track real tight. A little slow response in both pitch and roll. As long as I kept my level of aggressiveness down it was easy to track.
4	F1BD_S_3	5	Roll response is pretty quick. A little tendency to overshoot and oscillate in pitch. Back out of the loop in pitch. Pitch is slow and has a tendency to overshoot. I had to back out to prevent oscillations. Roll was quick and predictable. Level of aggressiveness was a factor in pitch, but not in roll.
5	F1BS_S_3	5	Roll is easy to follow. Pitch is more jerky with a tendency to overshoot. The pitch axis had a slow response. Had to fly the pitch axis slightly open loop to keep pitch overshoots form occurring. Roll was fine.
6	F1BR_S_3	4	Moderate compensation. I had to fight the tendency to fly high gain. The pitch response was slow but roll response was good.
7	F2BD_S_3	3	Roll response is not too bad. More sluggish in roll than I like it to be. Initial response is slow in both pitch and roll. Level of aggressiveness did not effect task. Needed a little larger input in roll to get the response I wanted.
8	F2BS_S_3	3	A little slower in pitch than I like it to be. A little slower in roll than I like it to be. A couple of overshoots in pitch every time it changes directions. Regarding compensation need larger inputs than I like to get the response I wanted. Tend to overshoot in both axis. Backing out of the loop reduced the number of overshoots I got.
9	F2BR_S_3	3	Minor overshoots in roll and pitch. A little slower than I like it to be in pitch and roll. Final response is pretty predictable. Small overshoots when I got real aggressive with it.
10	F2CD_S_3	5	A little slow in the roll response. Pitch seems a little quick...easy to stay in the desired criteria. Having a little more trouble in roll due to more overshoots. Slow in roll...tendency to overshoot. Level of aggressiveness in roll affected the number of overshoots.

Table H4: Pilot Comments During Airborne Evaluation (continued)

Have Pilot	Sortie 3	Pilot: Russ Sellers	Flight #: 0400
Record	**File Name**	**C-H Rating**	**Qualitative Comments**
11	F2CS_S_3	5	Slow in roll. Need quite a bit of input to get it to roll. Pitch isn't too bad. Quick response with a slight tendency to back out of the loop. Difficulty in roll is detracting my ability to track in pitch.
12	F2CR_S_3	4	Sluggish roll response. Pitch is pretty nice. Definitely slow in roll.
13	F2AD_S_3	2	Small overshoots in pitch. Pretty nice in roll...a tad slower than I like it to be. Fairly quick in roll and pitch. Fairly predictable. Level of aggressiveness wasn't a factor.
14	F2AS_S_3	3	A little slow in roll and pitch. Difficulty in acquiring due to slow roll. Needed more input than I wanted to get the response I wanted.
15	F2AR_S_3	2	Quite a bit of input required.
16	F3CD_S_3	5	Try to back out of the loop to stop oscillations in pitch and roll. A little more compensation is required in pitch rather than roll.
17	F3CS_S_3	6/5	A little slow in pitch. Tend to overshoot in roll. A little more difficult to dampen out oscillations. Extensive pilot compensation is necessary.
18	F3CR_S_3	5	Slow in pitch. A little tendency to oscillate in pitch. Slow in roll. When stick gets out of center, its hard to come out of the loop. I try to freeze the stick and come out of the loop to stop the oscillations.

Table H4: Pilot Comments During Airborne Evaluation (continued)

Have Pilot	Sortie 3	Pilot: Darcy Granley	Flight #: 0400
Record	**File Name**	**C-H Rating**	**Qualitative Comments**
19	F1AD_G_3	3	Good initial response in pitch. A little slow in the roll response. No tendency to PIO. Very predictable. Pretty large initial roll input required. Had to be a little more aggressive in roll.
20	F1AS_G_3	3	A little bit of oscillations in pitch. Response is satisfactory in pitch and roll. Predictable. No compensation required during task.
21	F1AR_G_3	3	A little imbalance in the control harmony. Roll more noticeable than pitch. Roll is slower. No compensation required.
22	F1DD_G_3	6	PIOing in the roll axis - oscillatory. Have to get in the open loop. Good initial response. Not very predictable at all. Had to come out of the loop after the initial response to prevent PIO.
23	F1DS_G_3	5	Good initial response in roll but oscillatory. Almost have to fly open loop in the roll axis. Hard to stabilize in this task. Workload is very high on this task. Can't relax a second. Poor level of predictability.
24	F1DR_G_3	6	A bit of a lag in the roll. Zig Zag in roll...very oscillatory. Very slow response after input. Tendency to overshoot. Got a little out of phase. Workload was high. Had to come out of the loop a little bit.
25	F2DD_G_3	5	Input in the roll axis tends to oscillate and overshoot. Need a large input in roll to get the aircraft going. Pitch seems O.K. Need to lead the input. Had to be fairly aggressive in roll to get it going, but then had to come out of it to prevent PIOing.
26	F2DS_G_3	4/5	Definite bobble in roll. Once acquired, you can reduce your workload. Lead input required to get the aircraft to roll.
27	F2DR_G_3	4	Definitely rolling back and forth here. Have to put a large input in roll. Maintaining pitch task was no problem. Had to be more aggressive in roll.
28	F3BD_G_3	2	Good response in roll. Once acquired and tracking, workload goes down. Pitch seems pretty good also. Response good in both axes. No tendency to overshoot. No compensation required.
29	F3BS_G_3	3	In this task a pitch lag is more noticeable. Need a more lead input to get it going. A little bit of undesirable motion in the pitch axis. Got a little bobble in pitch. I'm fairly aggressive in pitch. No real compensation required.
30	F3BR_G_3	3	Not too bad in roll. Have to put larger inputs in pitch to get going, and then need to come out of it. Roll was O.K. Because of large inputs required in pitch, it had a tendency to bobble.

Table H4: Pilot Comments During Airborne Evaluation (continued)

Have Pilot	Sortie 4	Pilot: Darcy Granley	Flight #: 0401
Record	**File Name**	**C-H Rating**	**Qualitative Comments**
1	F3BD_G_4	3	Easy to maintain track. Good roll response. Pitch rate O.K. Need a lead input (large initially). A little bit of a pitch bobble. Fairly predictable. A little bit of a lead input in pitch required to get the aircraft going. Little compensation required.
2	F3BS_G_4	4	Noticeable pitch bobble, which was the result of large lead inputs. Have to be fairly aggressive. Roll was O.K. Over controlling in pitch therefore not very predictable.
3	F3BR_G_4	3	Noticed poor control harmony due to pitch bobble. Don't need to be too aggressive in this task. Same comments as before.
4	F4CD_G_4	6	Bobble in pitch axis. Large input required in roll as well. Not too bad once you acquire track. Over controlling in pitch as well. Initial response in both axes is slow. Had to be aggressive in both axes. More difficulty in controlling the pitch.
5	F4CS_G_4	5	Bobbling in pitch. More pronounced in pitch than roll. No chance to relax. Need to be aggressive in both axes. Continually bobbling in pitch. Concentrating in pitch degrades performance in roll. Both axis objectionable.
6	F4CR_G_4	5	Getting bobble in pitch axis. Roll axis is not too bad. Need a large input in pitch, have to then come out of the loop a bit. Continual oscillation in pitch. Had to be aggressive in both axes.
7	FXAD_G_4	4	No real tendency to bobble in pitch. Fine tracking pretty easy in both axes. Roll needs a pretty good input to get going. Had to be a little more aggressive in pitch. Not much of a compensation required.
8	FXAS_G_4	5	A little bobble in pitch. Almost over controlling. Degrading my performance in roll. Had to be over aggressive, but then had to come out of the loop when you're getting close to fine tracking.
9	FXAR_G_4	4	Bad video and audio recording on the 8 mm tape. Easier task to perform. Deficiencies not as noticeable.
10	F3DD_G_4	6	Large roll input required. Over controlling in the roll axis. Have to be very aggressive. Slow response in roll axis. Over controlling resulted in PIO. Not very good handling qualities.
11	F3DS_G_4	5	Really over controlling in roll. Pitch doesn't seem to have same PIO tendency. Can't relax for a second. Need to come out of the loop a little bit. PIO big time.
12	F3DR_G_4	5	Fairly large input in pitch required to stay in desired criteria. Over controlling more extensive in roll rather than pitch. Need to come out of the loop in roll. Need to be fairly aggressive. Final response was not predictable at all.

Table H4: Pilot Comments During Airborne Evaluation (continued)

Have Pilot		Sortie 4	Pilot: Darcy Granley Flight #: 0401
Record	File Name	C-H Rating	Qualitative Comments
13	F4DD_G_4	5	Oh boy! Good ones here. Over controlling in roll. Bit of a bobble in pitch as well. Fine tracking is not too bad. Large inputs required on initial response, but predictability not to bad. Had to be fairly aggressive.
14	F4DS_G_4	5	A bobble is more noticeable in roll rather than pitch. Pretty large inputs required to get aircraft moving. Have to be very aggressive. Bit of a slow response. Tend to overshoot in roll more than pitch. Tendency to come out of the roll axis to keep from oscillating.
15	F4DR_G_4	4	Fairly large inputs required. Bobble in pitch is more noticeable than in roll. Initial response a bit slow. Tendency to over control and had to come out of the loop to avoid massive PIO.
16	F1DD_G_4	4	Roll response seems O.K. Fine tracking is fairly easy. Good response in pitch. No compensation technique required.
17	F1DS_G_4	4	A little over controlling in roll axis. Bobbling in roll axis. Pitch isn't too much of a problem. Large response in roll required.
18	F1DR_G_4	3	Not too bad in pitch. Roll more noticeable. Fine tracking is pretty straight forward. Can relax and ease off the stick a little bit.

Table H4: Pilot Comments During Airborne Evaluation (continued)

Have Pilot	Sortie 4	Pilot: Craig Edkins	Flight #: 0401
Record	**File Name**	**C-H Rating**	**Qualitative Comments**
19	F3AD_E_4		Roll feels pretty good, maybe a little sluggish. No real tendency to overshoot in pitch. Very light in the stick. Really lagging in roll. Spending a lot of time concentrating on the roll. Initial pitch response was quick. Had to shape my inputs in roll to get what I want.
2	F3AS_E_4		Find myself backing out in pitch. A little bobble in pitch. Roll performance isn't so noticeable now. Initial pitch response was quick. Roll was sluggish. Shaping the roll input to get what I want. Backing out in pitch.
21	F3AR_E_4		Bobbling tendency in pitch. A little sluggish in roll. Oscillating back and forth in pitch. Must accept errors in roll.
22	F3CD_E_4		A little overshoot in roll. Pitch feels pretty good so far. Lagging it all over the place in roll. Really lagging in roll. Slow, sluggish, final response not predictable. Using a lot of anticipation in both axis.
23	F3CS_E_4		Seems like its rolling quick enough. Definite bobbling tendency in pitch. Not a good airplane. Constantly in error. Trying to smooth it out. Level of aggressiveness doesn't reduce the error. Response was jerky and unpredictable. Total concentration by leading and anticipating.
24	F3CR_E_4		Almost controlling the aircraft with doublets, but if I miss I get a little bobble. Jerky and not predictable. Had to come out of the loop at times.
25	F4BD_E_4		Nice oscillations in pitch. Roll...so far so good. Can be fairly aggressive in pitch. Both axes quick but not predictable in pitch. Really concentrated in pitch and let roll go.
26	F4BS_E_4		Little oscillations in pitch. Errors all over the place. Roll errors when I concentrate on pitch. Pitch oscillations uncomfortable...makes me come out of the loop more. Pitch was very jerky and unpredictable. Almost ignored the roll axis.
27	F4BR_E_4		Every time I take my attention away in pitch it gets out of hand. That was a high work load. Pitch was quick enough but so oscillatory I had to fight it. Had to back out of the loop in pitch.
28	F1CD_E_4		Tendency to feel this out at first. Really tough to control in roll. Pitch is nice. I'm stair stepping my roll inputs. Pitch seems O.K. In roll, I had to put in big inputs and then guess when to take it out.
29	F1CS_E_4		Real sluggish in roll. Spend a lot of time working the roll. Work load is pretty high...maybe in pitch too. Flies like a heavy in many ways. High work load. Was not predictable. Tend to stair step in roll.

Table H4: Pilot Comments During Airborne Evaluation (continued)

Have Pilot Sortie 4 Pilot: Craig Edkins Flight #: 0401

Record	File Name	C-H Rating	Qualitative Comments
30	F1CR_E_4		So far so good in pitch. Really kind of nice. Roll...best way to handle it is to not get too picky. The more I enter the loop the worst it gets. Sluggish and unpredictable in roll. Came out of the loop slightly in roll.
31	F2AD_E_4		Oscillations in pitch are evident. Find myself doing the gross acquisition then letting it damp out. Roll is O.K. A little oscillatory in pitch and sluggish in roll.
32	F2AS_E_4		Tend to be bouncing around all over the place in pitch. Aircraft response is quick, jerky, and not predictable. Couldn't be as aggressive as I wanted to be in pitch. Had to come out of the loop a little bit.
33	F2AR_E_4		Everything seem fine. A little touchy in pitch. Tried to be real careful in pitch.
34	F2CD_E_4		Overshooting in roll. Had to step it out in roll. Lacks a little predictability. Was not predictable in roll. Had to slam my inputs in roll and then pull it out right away.
35	F2CS_E_4		A little bobbling in pitch...a little bit. I'm kind of backing out of the loop. Fine tracking is not good. Aircraft response is jerky. Slow in roll and O.K. in pitch. Not predictable. Undesirable motions all around.
36	F2CR_E_4		Fighting the pitch a bit. Jerky response. Oscillations were aggravating. Hard to fine track. Tend to back out of the loop to reduce oscillations.

Table H4: Pilot Comments During Airborne Evaluation (continued)

Have Pilot	Sortie 5	Pilot: Darcy Granley	Flight #: 0402
Record	File Name	C-H Rating	Qualitative Comments
1	FXCD_G_5	4	Pretty large input required to get the aircraft moving. A little bit of oscillation. Have to be fairly aggressive to get the aircraft going. Initial response a bit slow. No real compensation technique required.
2	FXCS_G_5	4	Fine tracking is not too bad. Need to put large input to get the aircraft going for large tracking bar movements. Tendency to over control with the large inputs.
3	FXCR_G_5	3	A little bit of oscillation. A little bit uncomfortable. Maintain an uncomfortable desired criteria. Slight oscillation back and forth was annoying. Not ideal but not undesirable.
4	FXBD_G_5	2	Fine tracking is fairly easy. Good initial response. Fairly predictable. Don't need to be too aggressive. No compensation required.
5	FXBS_G_5	2	Response seems to be initially good. Fairly easy to track target. Don't need to be aggressive. A little wavy motion but it does not compromise the task. Nice handling aircraft.
6	FXBR_G_5	1	Very slight oscillation but it does not detract you from the task. No compensation required. Very straight forward.
7	F1XD_G_5	1	Good initial response. Very quick. Fairly predictable. Don't have to be aggressive at all. Fairly easy task right now. Very predictable. Quick and predictable.
8	F1XS_G_5	2	Same comments as before. Good initial response. Don't have to be aggressive at all. Just a slight bobble occasionally, but negligible deficiencies.
9	F1XR_G_5	2	Good response. I don't seem to be over controlling the stick. This isn't very difficult at all. Initial response is good and predictable.
10	F2XD_G_5	2	A little bit of a bobble when you acquire the target. Not really objectionable, but you can see it. No real compensation right now. A little bit of an oscillation, but it does not degrade you from the task.
11	F2XS_G_5	2/3	Good initial response. A little bit of a bobble. Don't have to be aggressive at all. Same comments as before.
12	F2XR_G_5	2	Good response. Pilot work load is probably low. Gains going way down for the pilot. Good handling characteristics. Slight oscillations to keep in desired criteria.
13	F3XD_G_5	3	Fine tracking doesn't seem too bad. Not a quick initial response. Sort of a lead input, but fine tracking was easy. Final part was fairly predictable. No compensation required.
14	F3XS_G_5	3	No tendency to oscillate. Find myself a little lagging with my inputs. Initial response a bit slow. Wasn't overly aggressive. Gave it stick raps to keep it close.

Table H4: Pilot Comments During Airborne Evaluation (continued)

Have Pilot			Sortie 5 Pilot: Darcy Granley Flight #: 0402
Record	File Name	C-H Rating	Qualitative Comments
15	F3XR_G_5	3	A little bit of an oscillation there. Work load is down now. Sort of came out of the loop to knock down the oscillations. A little bit of over controlling my stick.
16	FXDD_G_5	5	Gross acquisition seems to be a bit of a problem. Definitely annoying. Have to put in a large input to get it going and then take it out early. Kind of a slow response. Tried to guess when to take the input out. Found it very annoying.
17	FXDS_G_5	4	Large lead input required to get aircraft going. Oscillation is very annoying. Have to come out of the loop to get rid of the oscillations. Can't relax at all. High work load throughout the task.
18	FXDR_G_5	4	Minor oscillations here. Coming out of the loop slightly because of back and forth oscillations. Initial response is a little bit slow. Tendency to oscillate back and forth. High work load throughout the task.
19	F4AD_G_5	4	Slight bobble in pitch. Roll doesn't seem too bad. Pitch seems slightly damped. Continually bobbling back and forth. Pitch seems fairly predictable. The initial pitch response is fairly quick. Roll was a bit slow. Oscillations in pitch detracted my performance in roll. Put in large inputs in roll to get the aircraft rolling.
20	F4AS_G_5	4/5	Definite bobble in pitch. Roll response seems O.K. Over controlling in pitch. Putting in big inputs. Fairly large stick raps in pitch which degrade my concentration on roll.
21	F4AR_G_5	3	Annoying oscillations in pitch. Not working too hard right now. Sort of relaxing right now a little bit. Fairly easy doing the task. Slight bobble in pitch.

Table H4: Pilot Comments During Airborne Evaluation (continued)

Have Pilot Sortie 5 Pilot: Craig Edkins Flight #: 0402			
Record	File Name	C-H Rating	Qualitative Comments
22	F4XD_E_5	4	A little bobbling tendency here. Shaping my inputs to acquire target. Definite lag or delay in it. Initial response was slow which made me tend to overshoot. Could be aggressive so long I wasn't fine tracking.
23	F4XS_E_5	5	Tend to overshoot when I correct my fine error. Tend to back out a little bit. Definitely have a lot of oscillations when I fine track. Jerky, not predictable. Couldn't be too aggressive.
24	F4XR_E_5	5	Trying to be real smooth. Try to make open loop inputs, to prevent oscillations. Little higher work load. Takes a bit of compensation to fly the aircraft. Pretty objectionable. Jerky. Had to be unaggressive by flying open loop.
25	FXAD_E_5	1	Can zero it out at all times. Really good airplane. Being really aggressive. Quick. Predictable. Compensation wasn't factor.
26	FXAS_E_5	1	I can raise my level of aggressiveness to reduce my error, which is kind of nice. Can make pretty quick inputs. Quick response. Predictable. No compensation required.
27	FXAR_E_5	1	I can be real picky on this. Being fairly aggressive. No undesirable motions. No tendency to overshoot. Same comments. Real easy to fly.
28	F4BD_E_5	5	A little oscillation tendency in pitch so far. In the roll axis I find myself stair stepping a bit. Have to back out in aggressiveness which cuts down on the oscillations. Pitch seemed quick but oscillatory. Work load was fairly high and I had to anticipate.
29	F4BS_E_5	5	Trying to be easy with it. Can't be as aggressive as I want to be. Pitch axis has an oscillatory tendency. Roll oscillations are pretty bad. Feel like I'm getting close to desired criteria. Lack of predictability. Compensation was moderate, had to shape my inputs.
30	F4BR_E_5	5	Bobbling in pitch again. Sort of ignoring the roll axis which I shouldn't be doing. On all sides of the pitch. Roll is sluggish to me. Had to back out of loop and reduce my aggressiveness.
31	F2BD_E_5	4	Fairly aggressive with it. Don't like the motion I'm getting. Had to back out slightly. Moderate compensation. Sluggish in roll. Level of aggressiveness was low.
32	F2BS_E_5	4	Oscillating in pitch. Sluggishness in roll. Taking three inputs to do one acquisition in pitch. Bobbling tendency hurt predictability. Backed out of the loop sightly.
33e	F2BR_E_5	3	Need to be gentle in pitch. Doing the task fairly easily. Bobbling was slight. Roll axis was pretty nice. Fairly aggressive in roll not so much in pitch.

Table H4: Pilot Comments During Airborne Evaluation (continued)

Have Pilot Sortie 5 Pilot: Craig Edkins Flight #: 0402			
Record	File Name	C-H Rating	Qualitative Comments
34	F4DD_E_5	7	Have to be real easy in roll. Big lead to catch it. Hard to tell what's going on in pitch. The roll axis is taking all my concentration. Pitch seemed O.K., although it wasn't predictable. Had a tendency to overshoot. To compensate I had to really come out of the loop. I couldn't be aggressive.
35	F4DS_E_5	6	Real easy in roll. Trying to control with stair stepping. Pitch doesn't take much attention. Sluggish in roll. Oscillates. Not predictable. Had to come out of the loop.
36	F4DR_E_5	6	Very undesirable roll mode. Even getting some bobbling in pitch. Almost ignoring the pitch axis. The roll axis is not predictable at all. Pitch was quick.
37	F3AD_E_5	4	Slow in roll. Need to start shaping my inputs. Takes a little more work. The roll axis takes my concentration from the pitch axis. Had a nice acquisition in the pitch axis. Backed out of the loop in the pitch axis.
38	F3AS_E_5	4	The roll seems to be doing fine in fine tracking. Doing O.K. in pitch too. When I get large errors in the roll axis it bugs me. Bobbling in pitch now. I'm backing off in aggression but I'm in the loop.
39	F3AR_E_5	3	Pitch has a slight bobble. Used minimal pilot compensation. Lacked a little predictability.
40	F2DD_E_5	7	Wow! Big roll. I can not be aggressive at all in the roll axis. I gave up on the task to get control of the aircraft Pitch seems to be O.K. Roll really sucks. If I didn't give up on the task, it would have gone divergent. Initial response in the pitch axis was O.K. Roll response was slow. Wasn't predictable.
41	F2DS_E_5	6	Kind of going easy with it. Smoothly getting rid of errors. Best control strategy. Work load was tolerable. The roll axis got all my attention. Had to back out. Couldn't be very aggressive.
42	F2DR_E_5	7	Real touchy in the roll axis. Seems like you're in a boat. Rock and roll...back and forth. Rolling around a central pitch. Roll was oscillatory. Not predictable. Had to back out of the loop. Total concentration on the roll axis.

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APPENDIX I

COOPER-HARPER RATING GRAPHS

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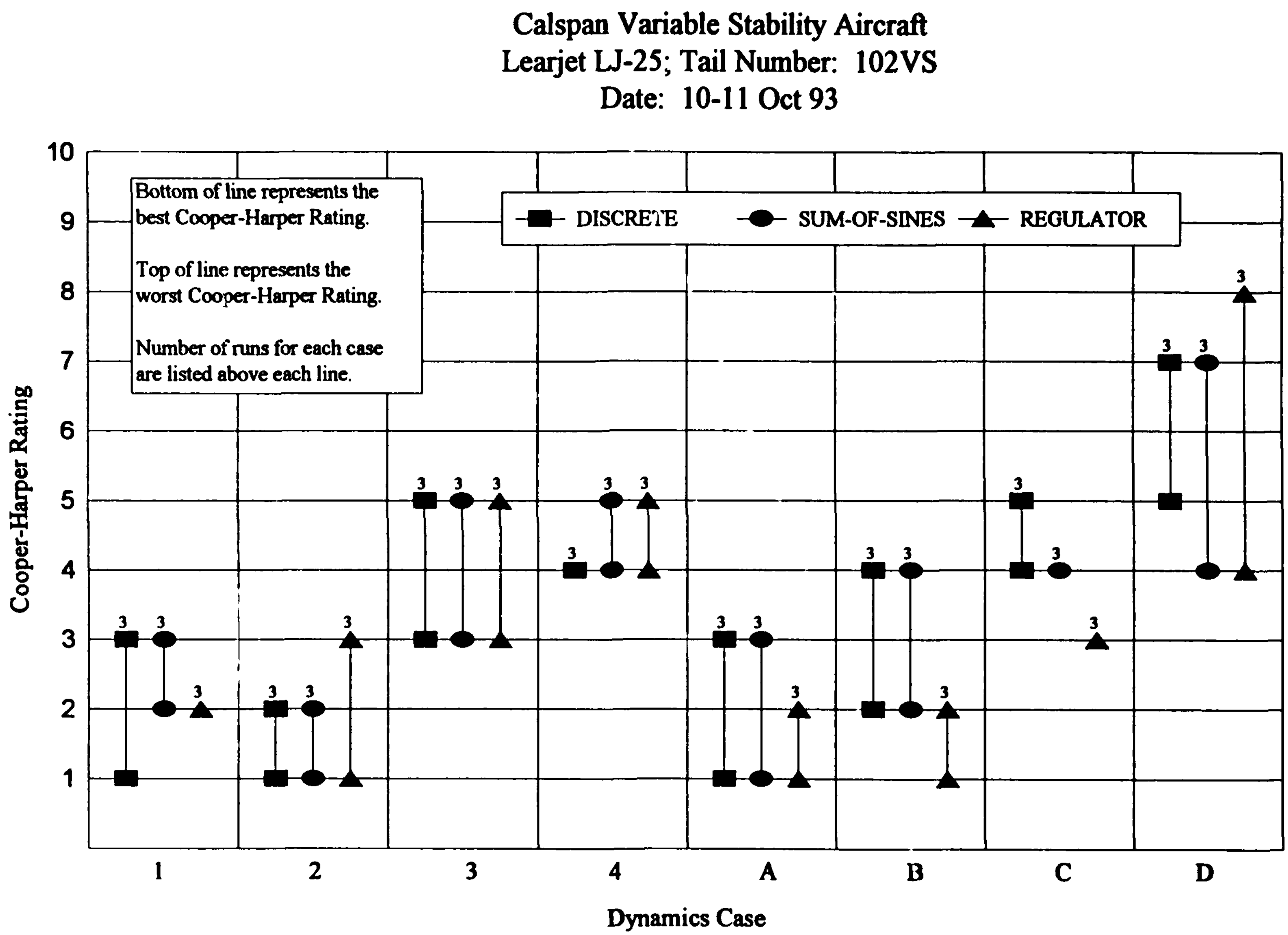

Figure I1: Cooper-Harper Ratings by Tracking Task (Airborne Data - 1 of 3)

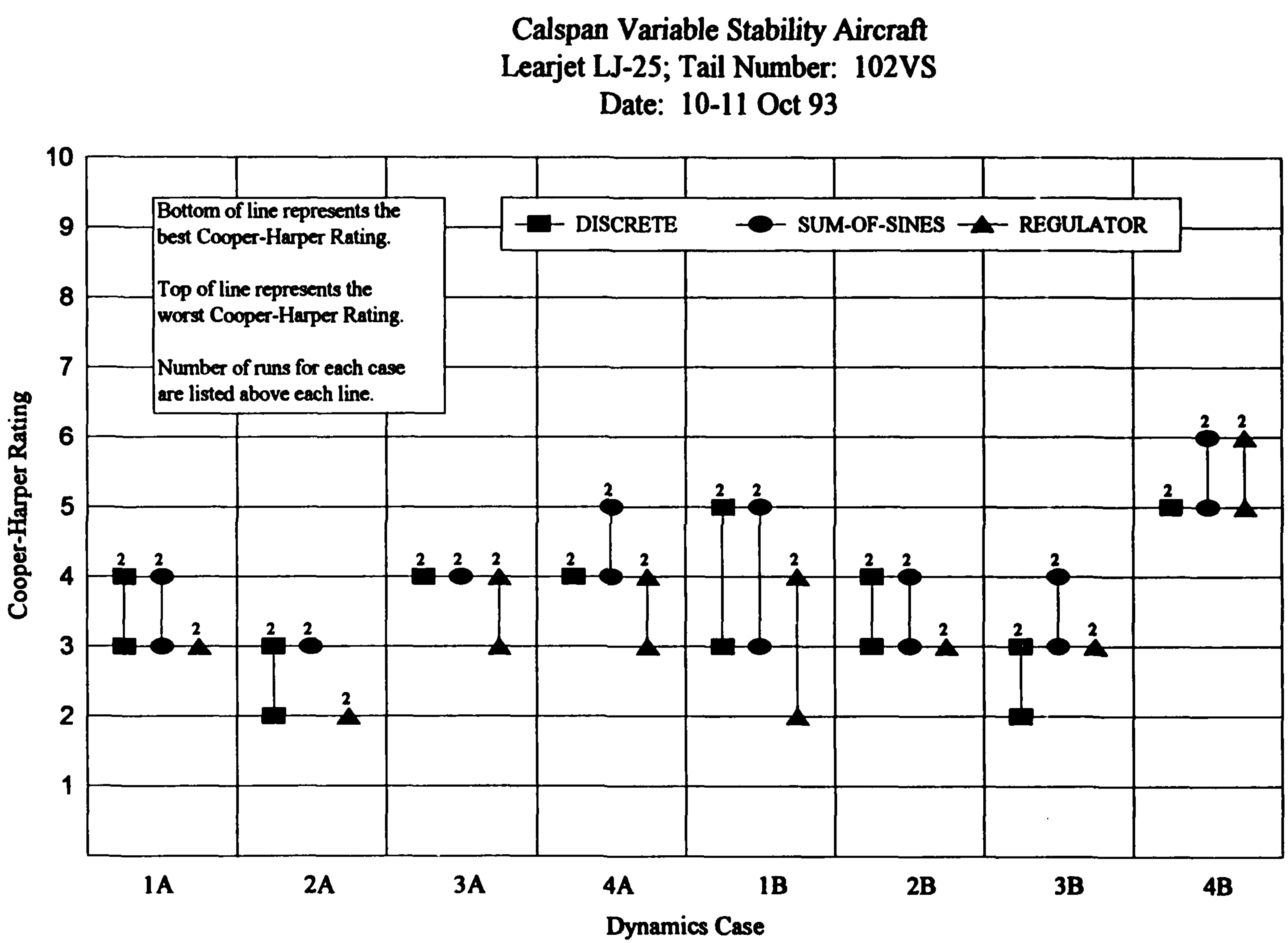

Figure I2: Cooper-Harper Ratings by Tracking Task (Airborne Data - 2 of 3)

Calspan Variable Stability Aircraft
Learjet LJ-25; Tail Number: 102VS
Date: 10-11 Oct 93

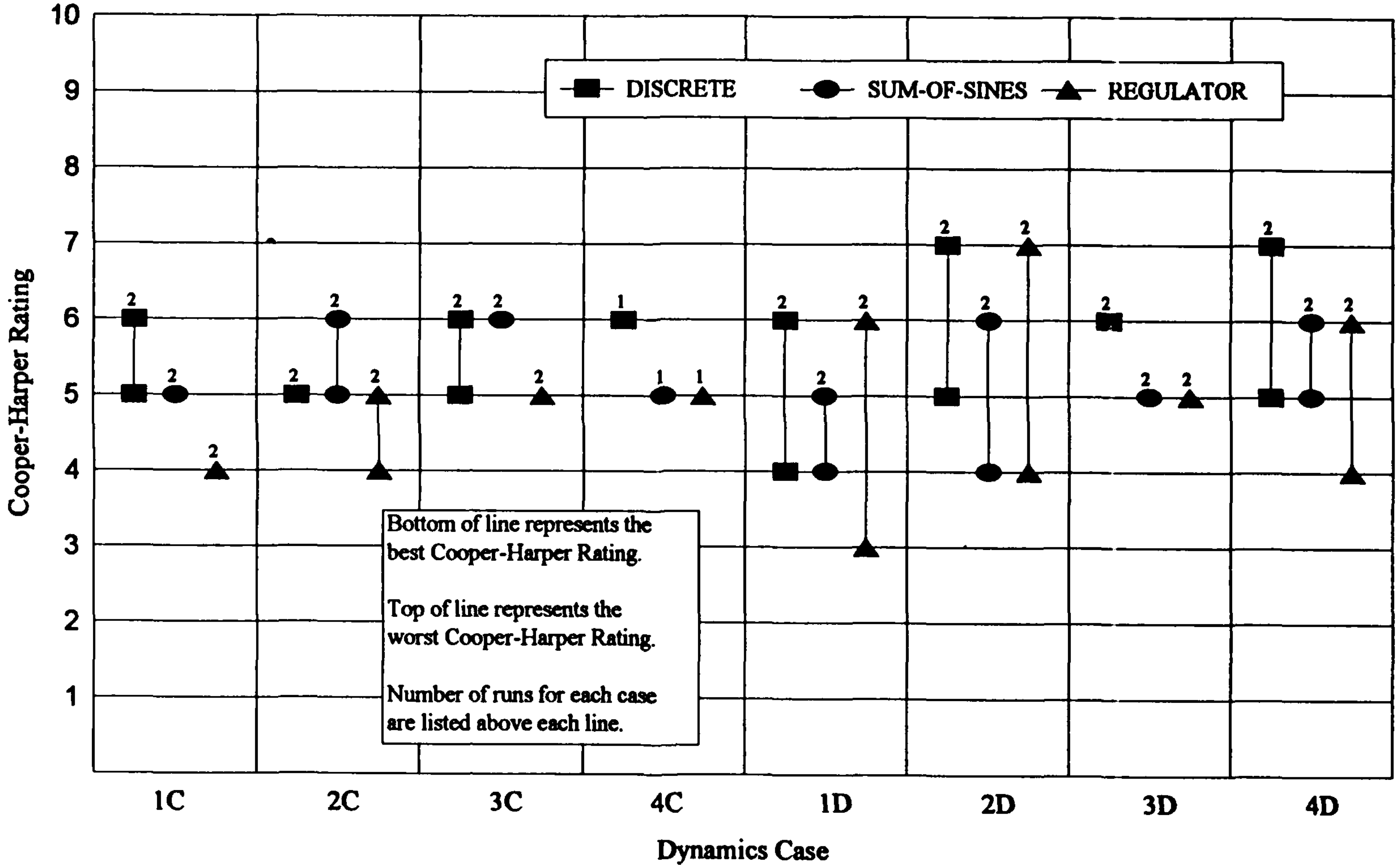

Figure I3: Cooper-Harper Ratings by Tracking Task (Airborne Data - 3 of 3)

Calspan Variable Stability Aircraft
Learjet LJ-25; Tail Number: 102VS
Date: 10-11 Oct 93

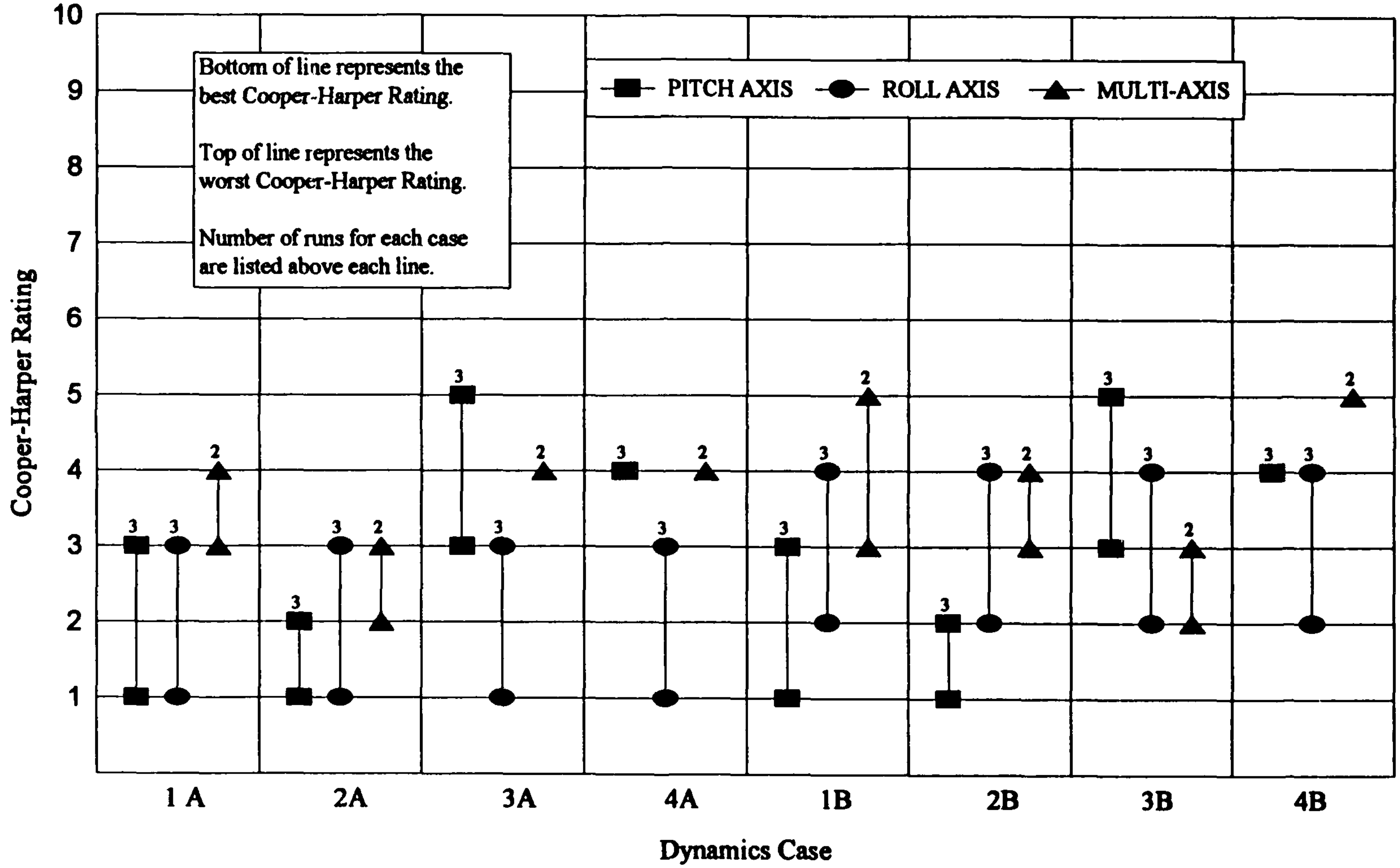

Figure I4: Comparison of Single and Multi-Axis Cooper-Harper Ratings (1 of 2)

Calspan Variable Stability Aircraft
Learjet LJ-25; Tail Number: 102VS
Date: 10-11 Oct 93

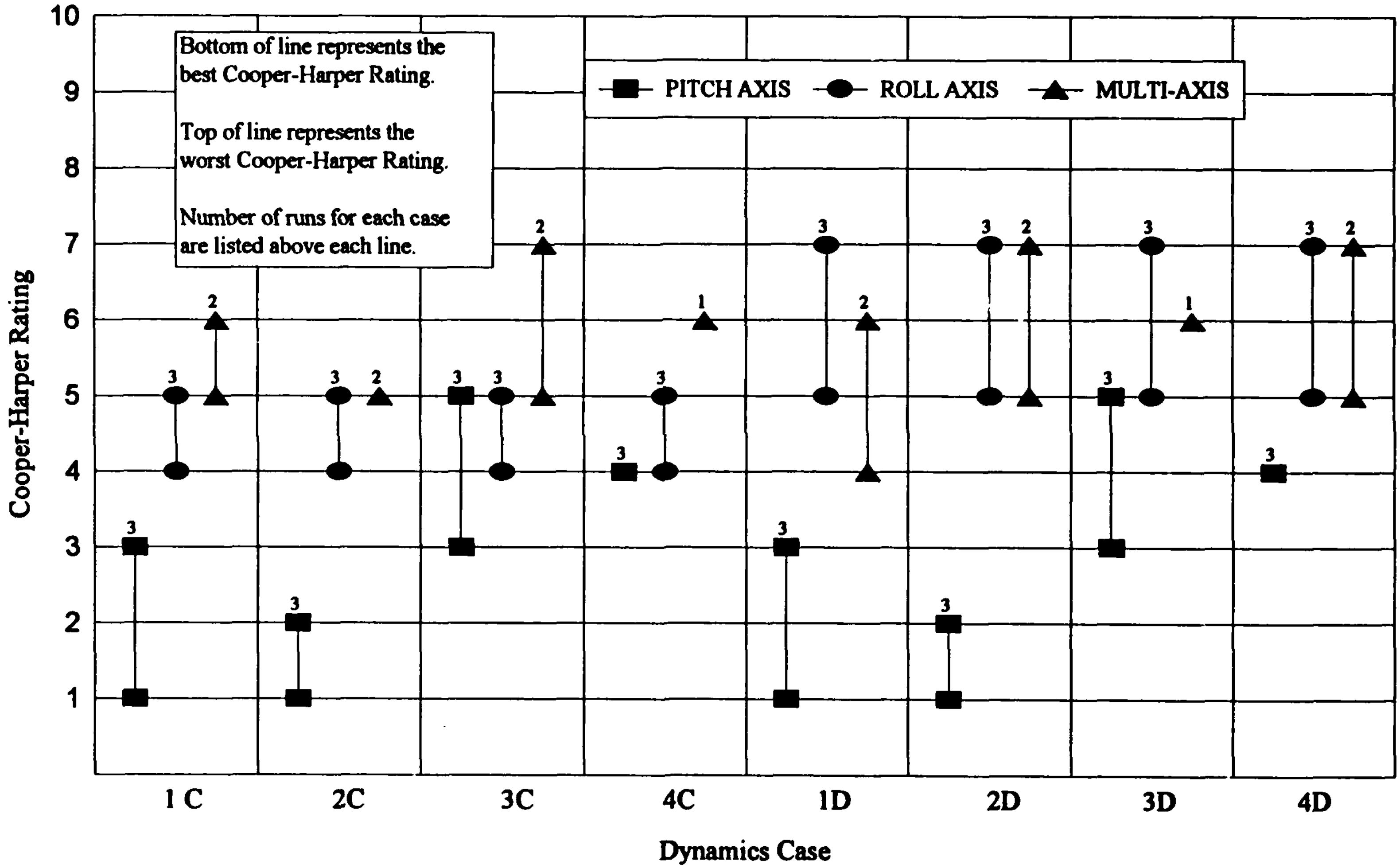

Figure I5: Comparison of Single and Multi-Axis Cooper-Harper Ratings (2 of 2)

Product Rule Predictions

The following formulas were used to determine the product rule estimations in Figures I6 through I9 (see Reference 5 for a detailed explanation).

Classical Product Rule:

$$Rating = 10 + \frac{1}{8.3}(R_\theta - 10)(R_\phi - 10)$$

Revised Product Rule:

$$Rating = 8.3 - \frac{1}{6}(R_\theta - 7.8)(R_\phi - 10)$$

Elliptical Product Rule:

$$Rating = -1.2 + 1.26R_\theta + 1.95R_\phi - 0.17R_\theta R_\phi + 0.009R_\theta^2 + 0.049R_\phi^2$$

Where,

R_θ = Pitch Axis Cooper-Harper Rating
R_ϕ = Roll Axis Cooper-Harper Rating
Rating = Predicted Multi-Axis Cooper-Harper Rating

Calspan Variable Stability Aircraft
Learjet LJ-25; Tail Number: 102VS
Date: 10-11 Oct 93

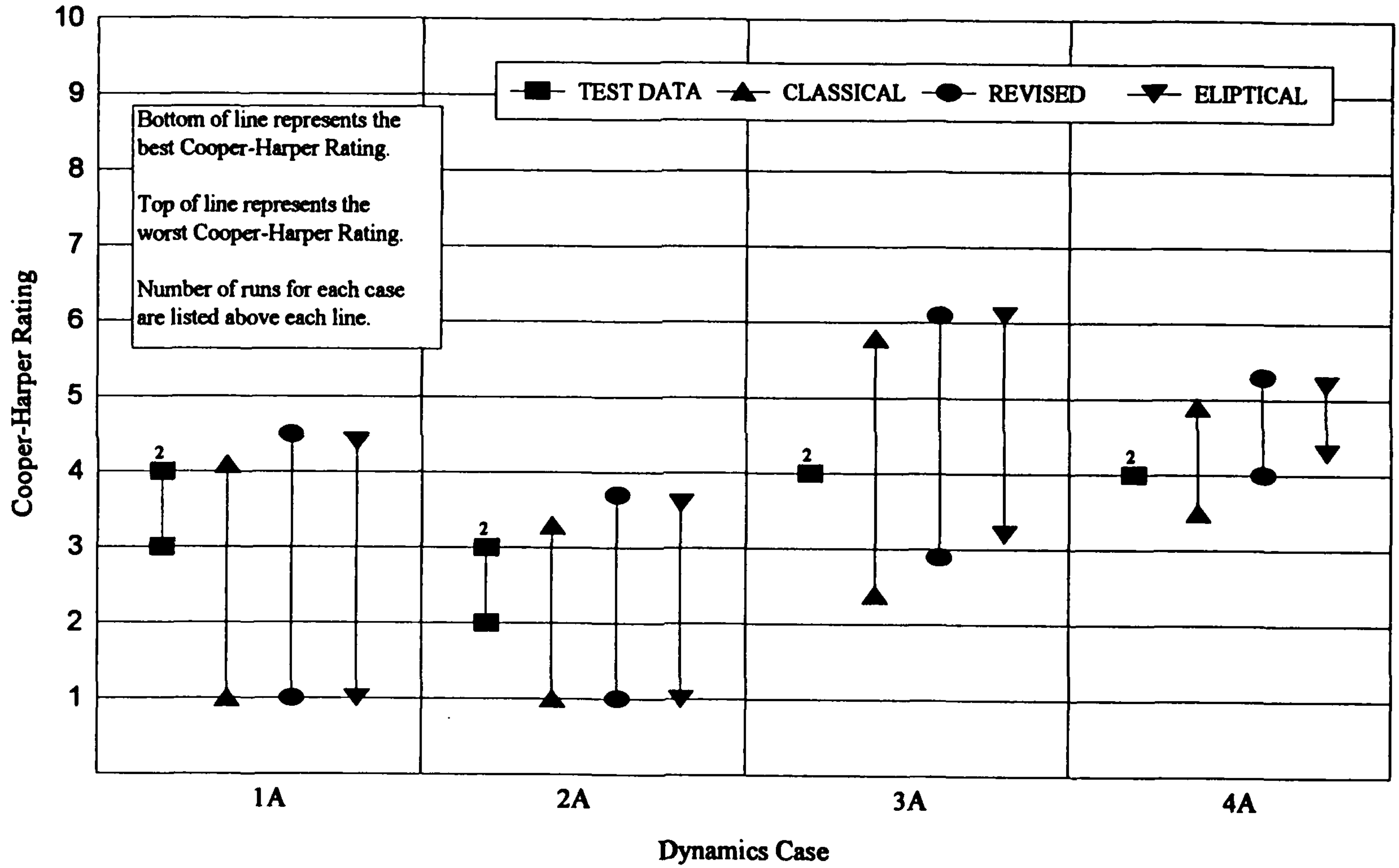

Figure I6: Product Rule Predictions (Airborne Discrete Task - 1 of 4)

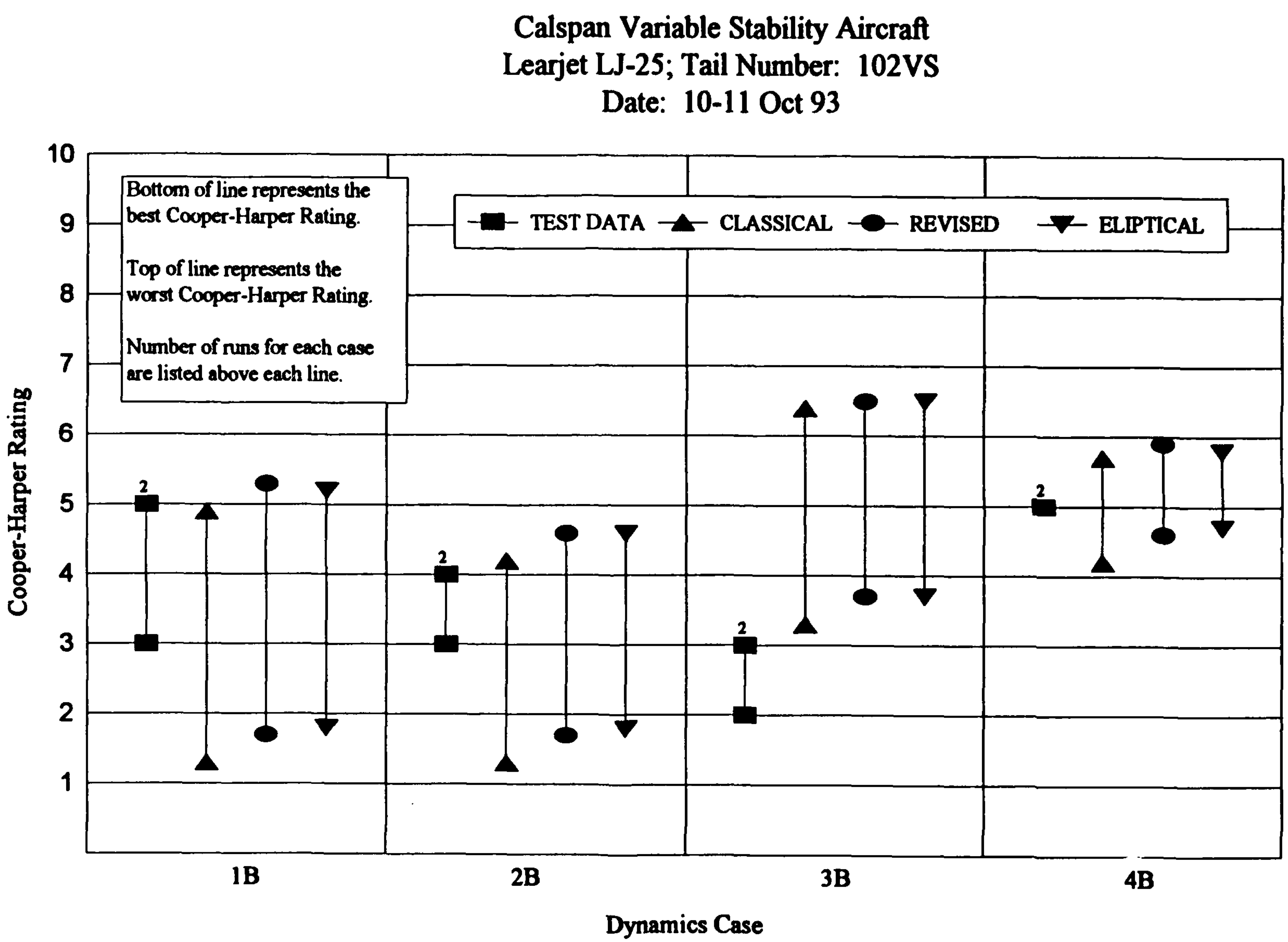

Figure I7: Product Rule Predictions (Airborne Discrete Task - 2 of 4)

Calspan Variable Stability Aircraft
Learjet LJ-25; Tail Number: 102VS
Date: 10-11 Oct 93

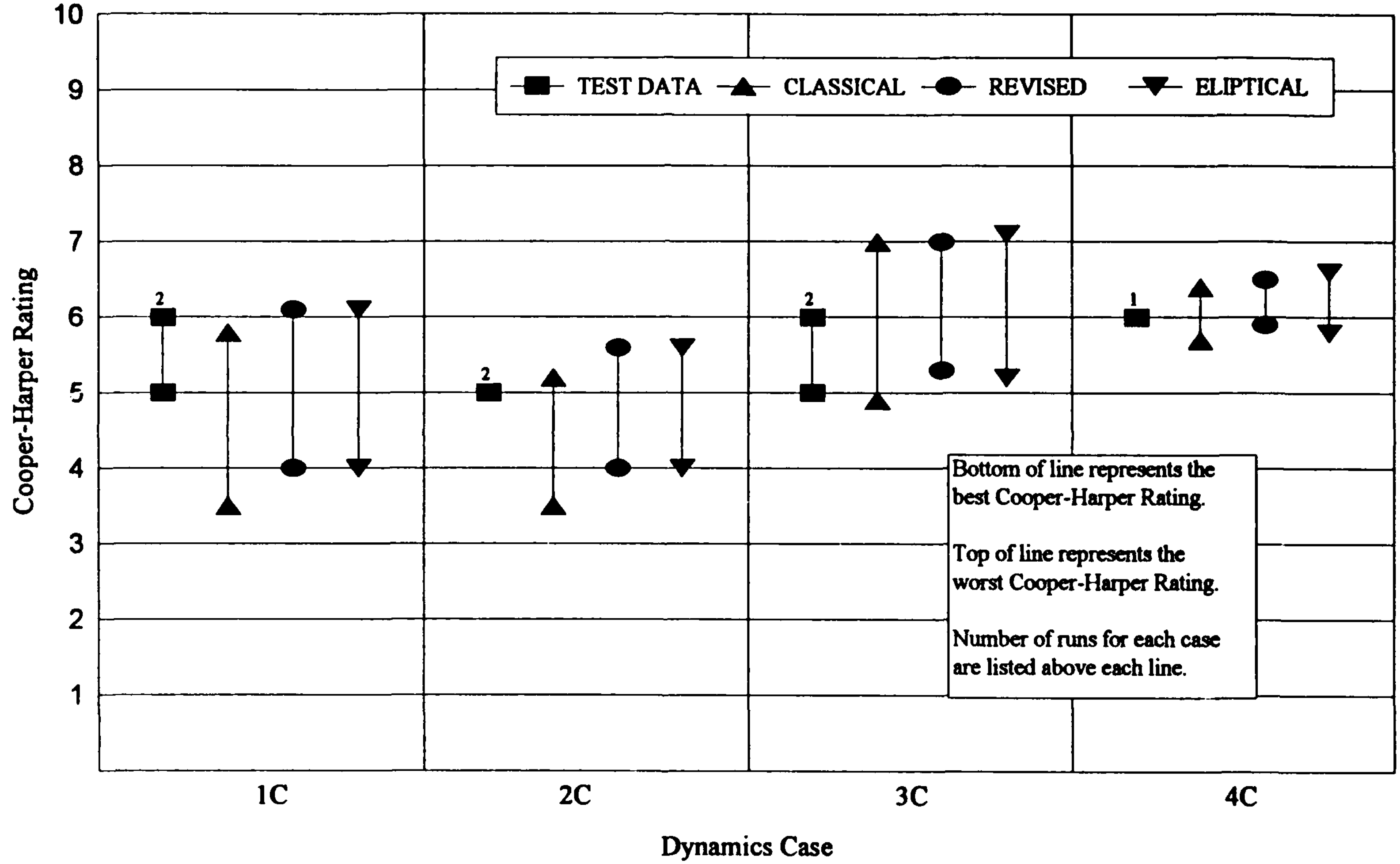

Figure I8: Product Rule Predictions (Airborne Discrete Task - 3 of 4)

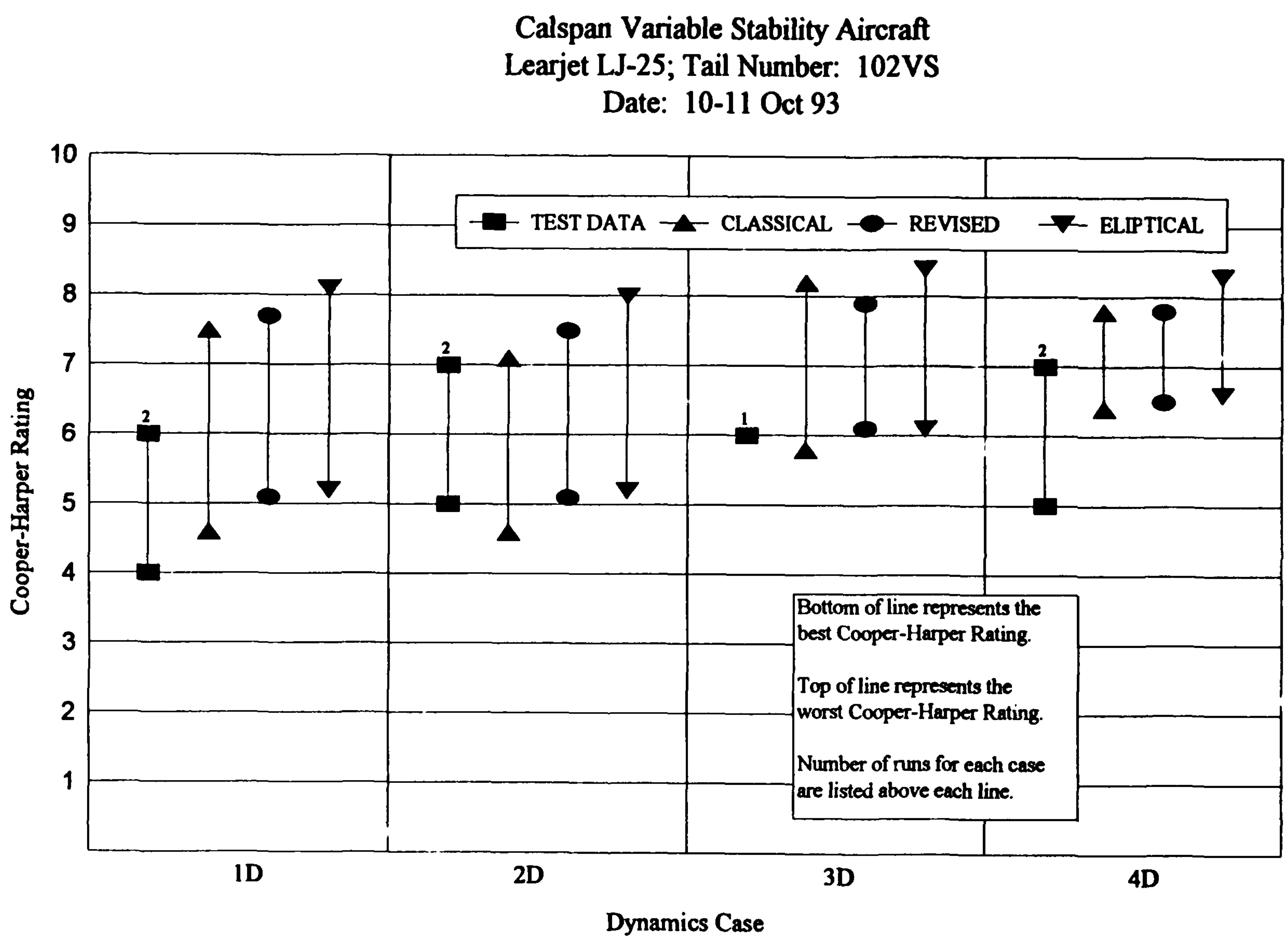

Figure I9: Product Rule Predictions (Airborne Discrete Task - 4 of 4)

Calspan Variable Stability Aircraft
Learjet LJ-25; Tail Number: 102VS
Date: 10-11 Oct 93

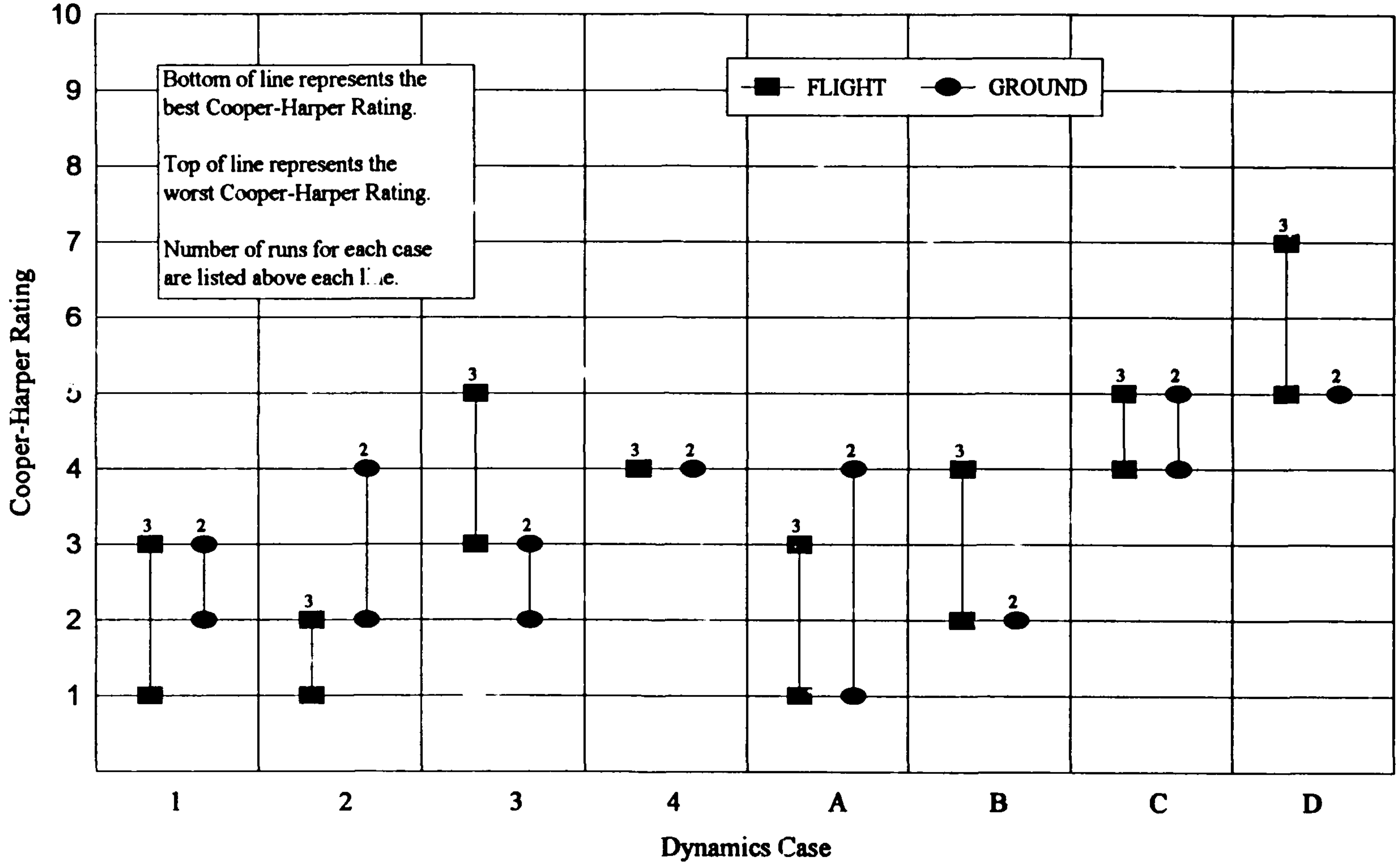

Figure I10: Comparison of Ground and Airborne Cooper-Harper Ratings (1 of 3)

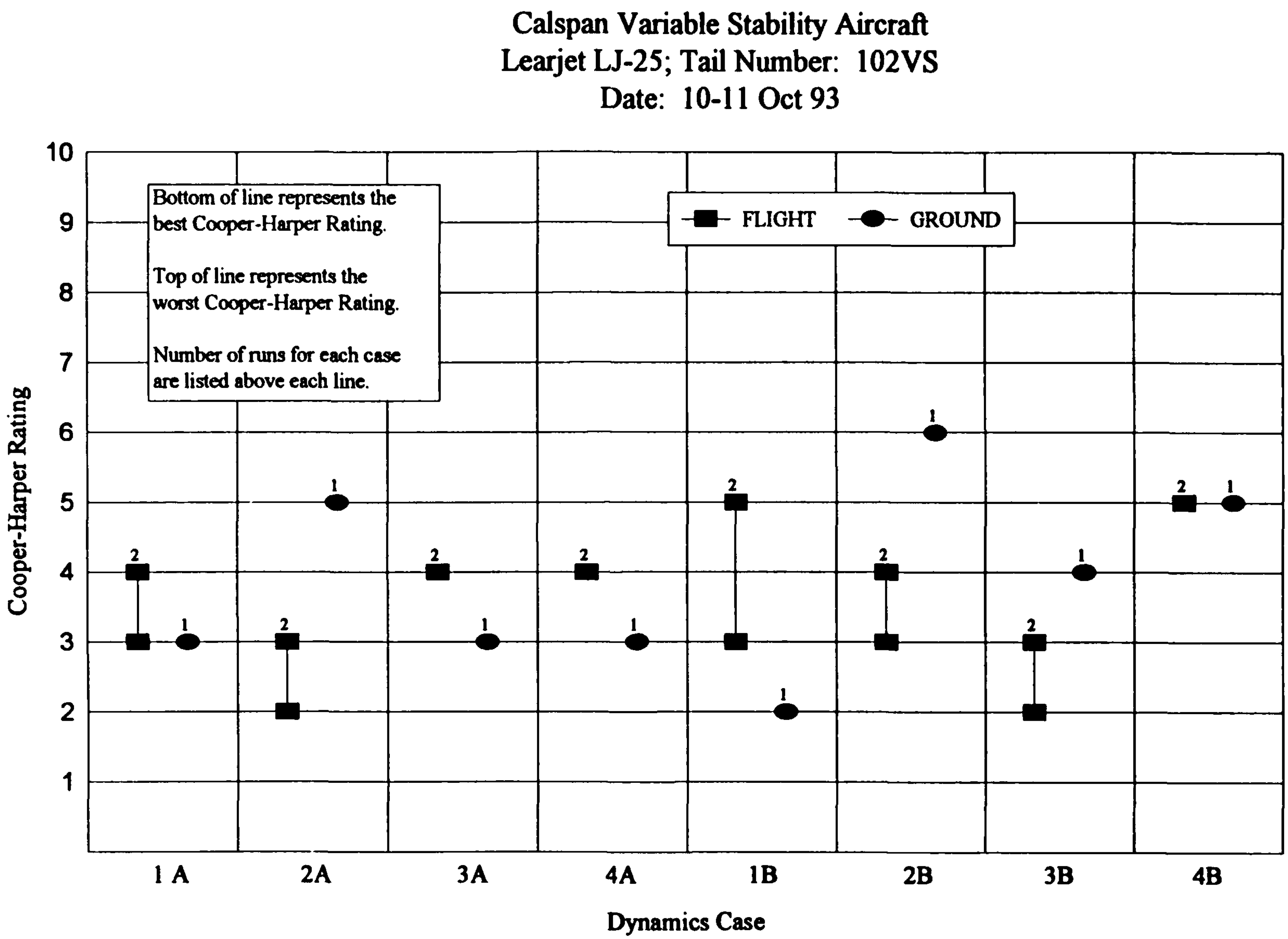

Figure I11: Comparison of Ground and Airborne Cooper-Harper Rating (2 of 3)

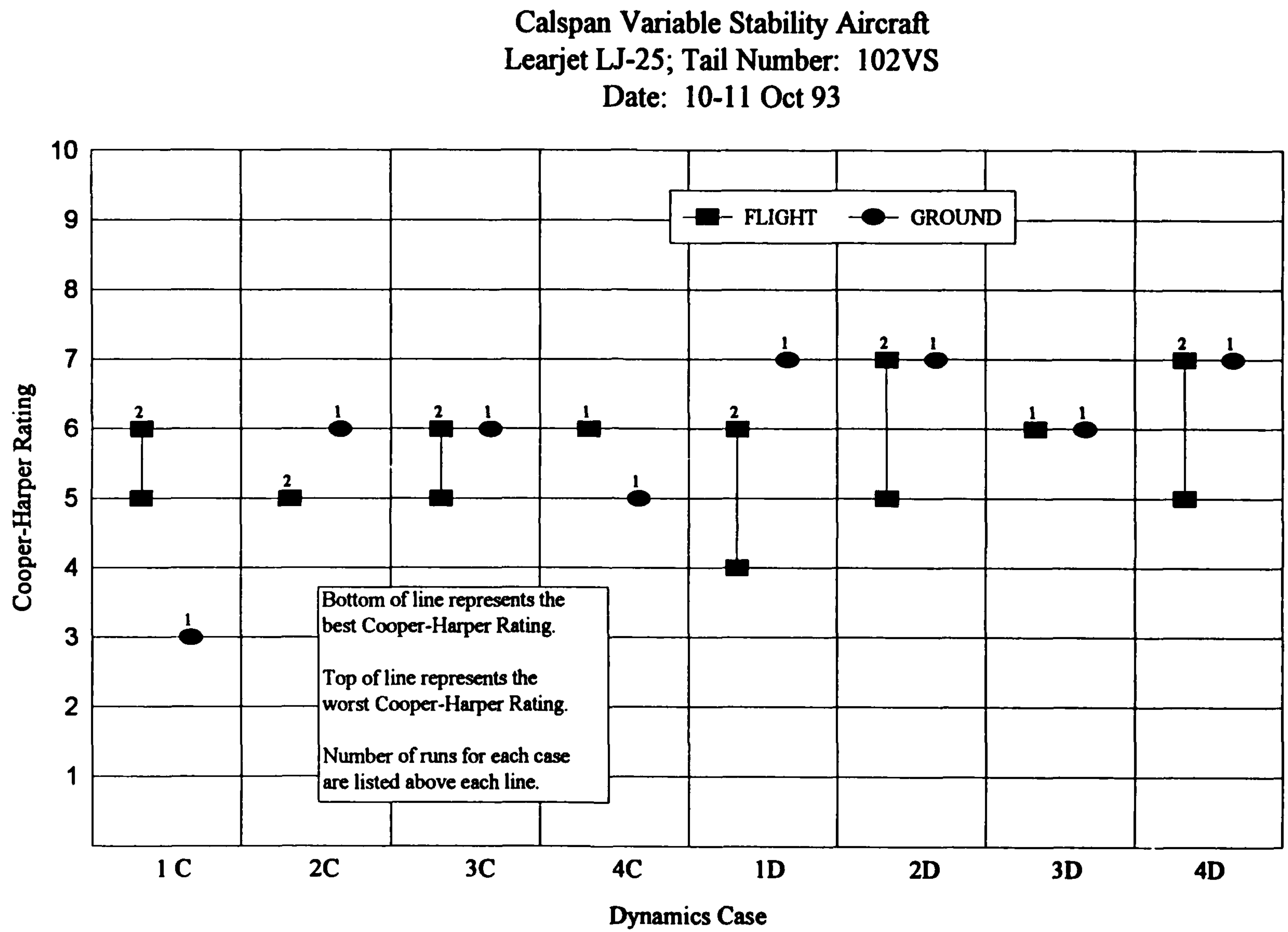

Figure I12: Comparison of Ground and Airborne Cooper-Harper Rating (3 of 3)

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APPENDIX J

DISCRETE TRACKING TASK TIME HISTORIES AND PILOT DELAY DATA

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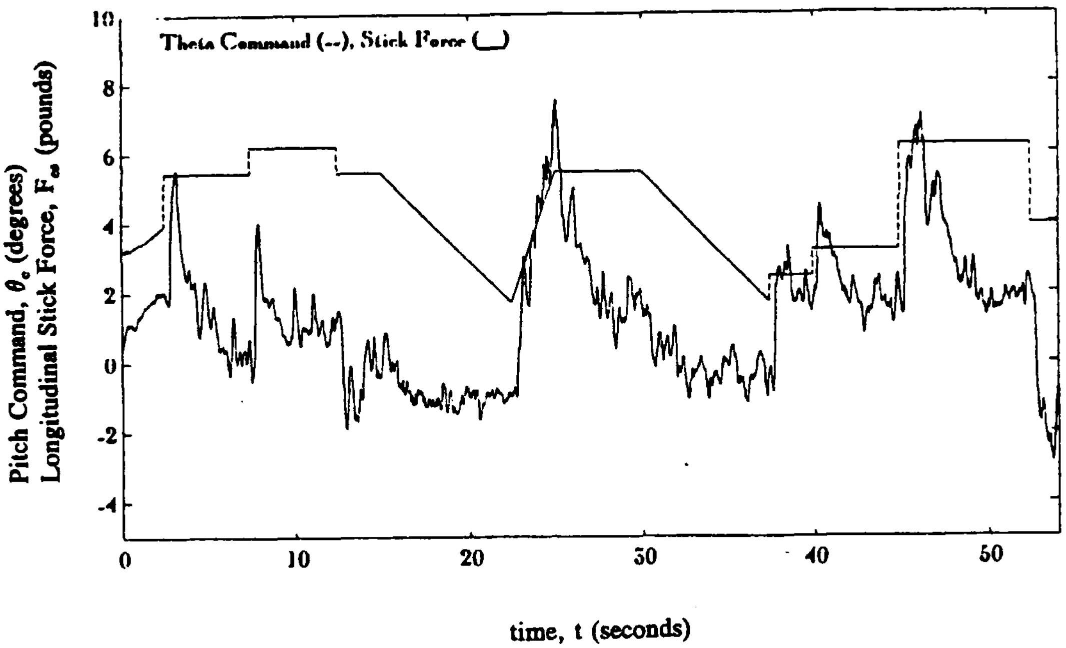

Figure J1: Discrete Tracking Task Time History

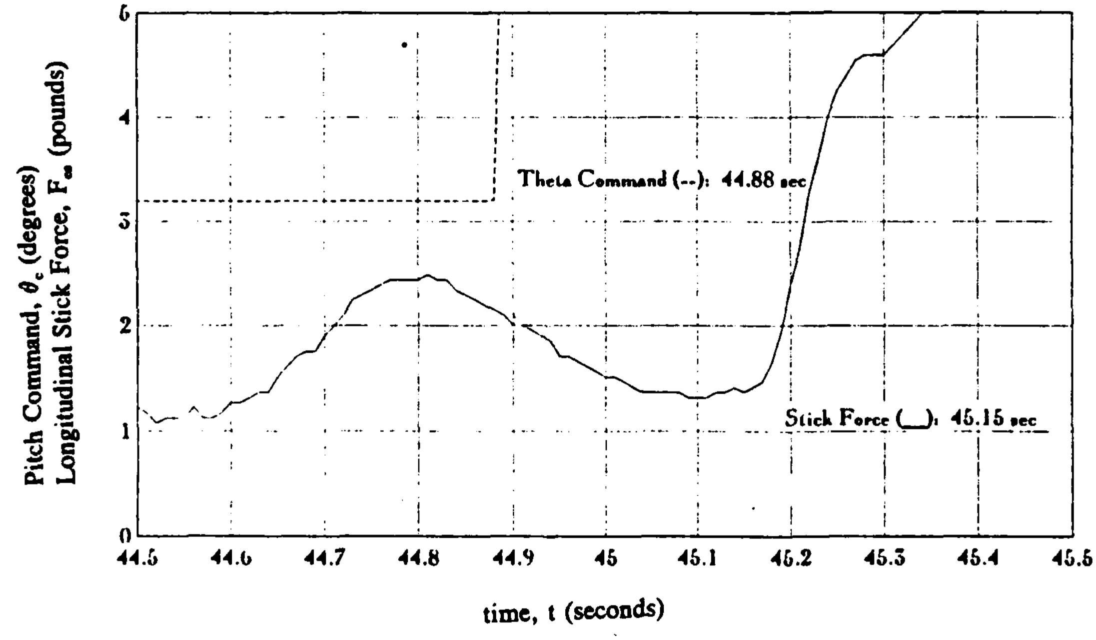

Figure J2: Discrete Tracking Task Time History - Expanded Scale

Table J1: Pilot Delay - Task Command to Initial Stick Force
Airborne Single Axis Tracking Task

Pilot	Case 1	Case 2	Case 3	Case 4	Case A	Case B	Case C	Case D	Mean Delay by Pilot
G	0.28 0.26	0.25	0.26 0.26	0.31	0.25	0.26	0.27	0.28	0.27
S	0.29	0.28	0.24	-	-	-	-	-	0.27
E	-	0.25	-	0.28 0.27	0.30 0.29	0.30 0.26	0.27 0.25	0.26	0.27
Mean Delay by Case	0.28	0.26	0.25	0.29	0.28	0.27	0.26	0.27	

Note: Add 0.1 seconds to all values for delay between task command and initial stick movement

APPENDIX K

SELECTED SINGLE AXIS FORCE AND DISPLACEMENT PILOT RESPONSE DATA

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Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 10 Oct 93; Pilot: S; Sortie #2
Sum-of-Sines Tracking Task; Case 1 (See Appendix D)
Airborne Data

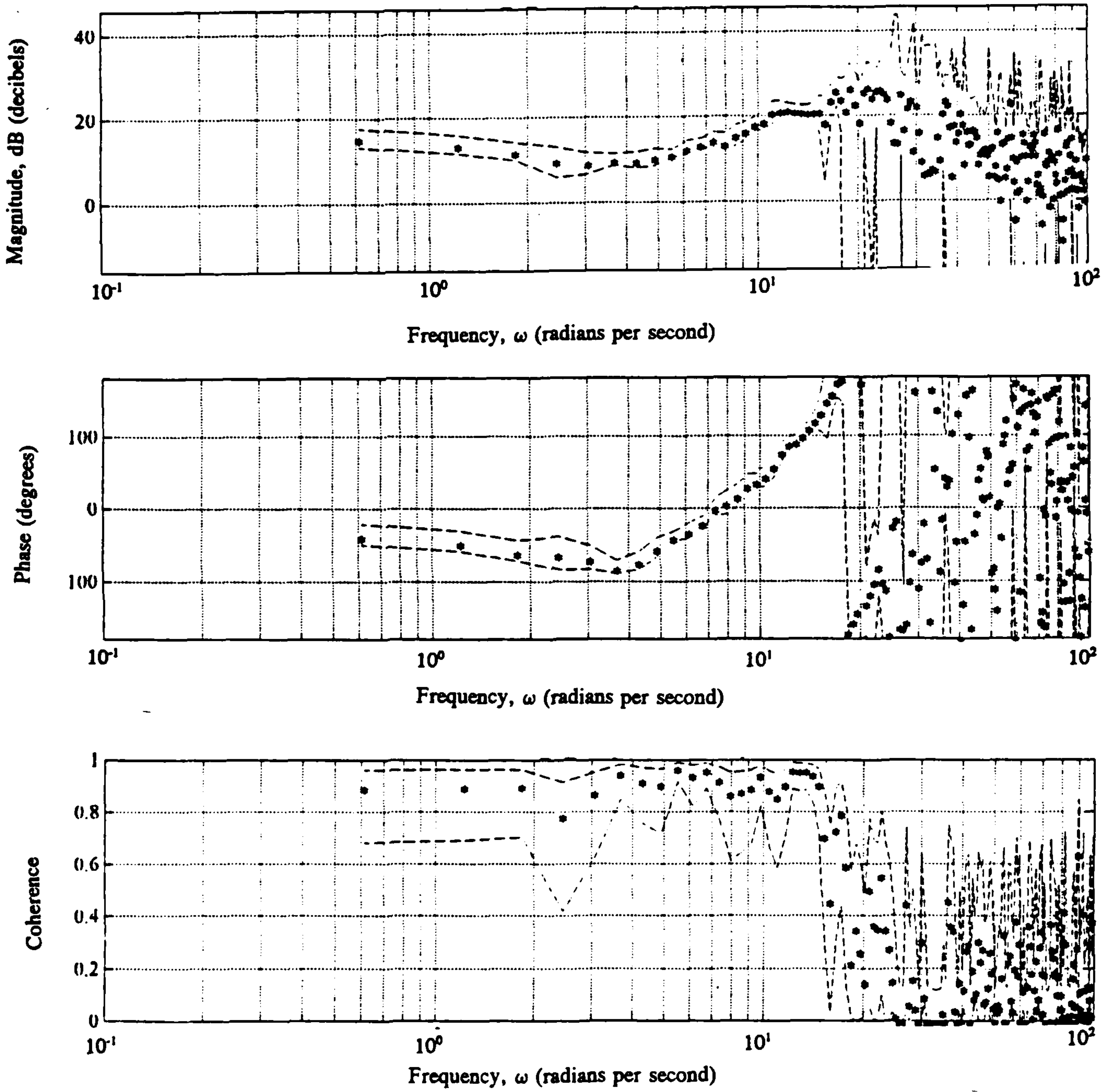


Figure K1: Frequency Response Analysis -
Longitudinal Stick Force to Task Error (File F1XS_S_2)

Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 10 Oct 93; Pilot: S; Sortie #2
Sum-of-Sines Tracking Task; Case 1 (See Appendix D)
Airborne Data

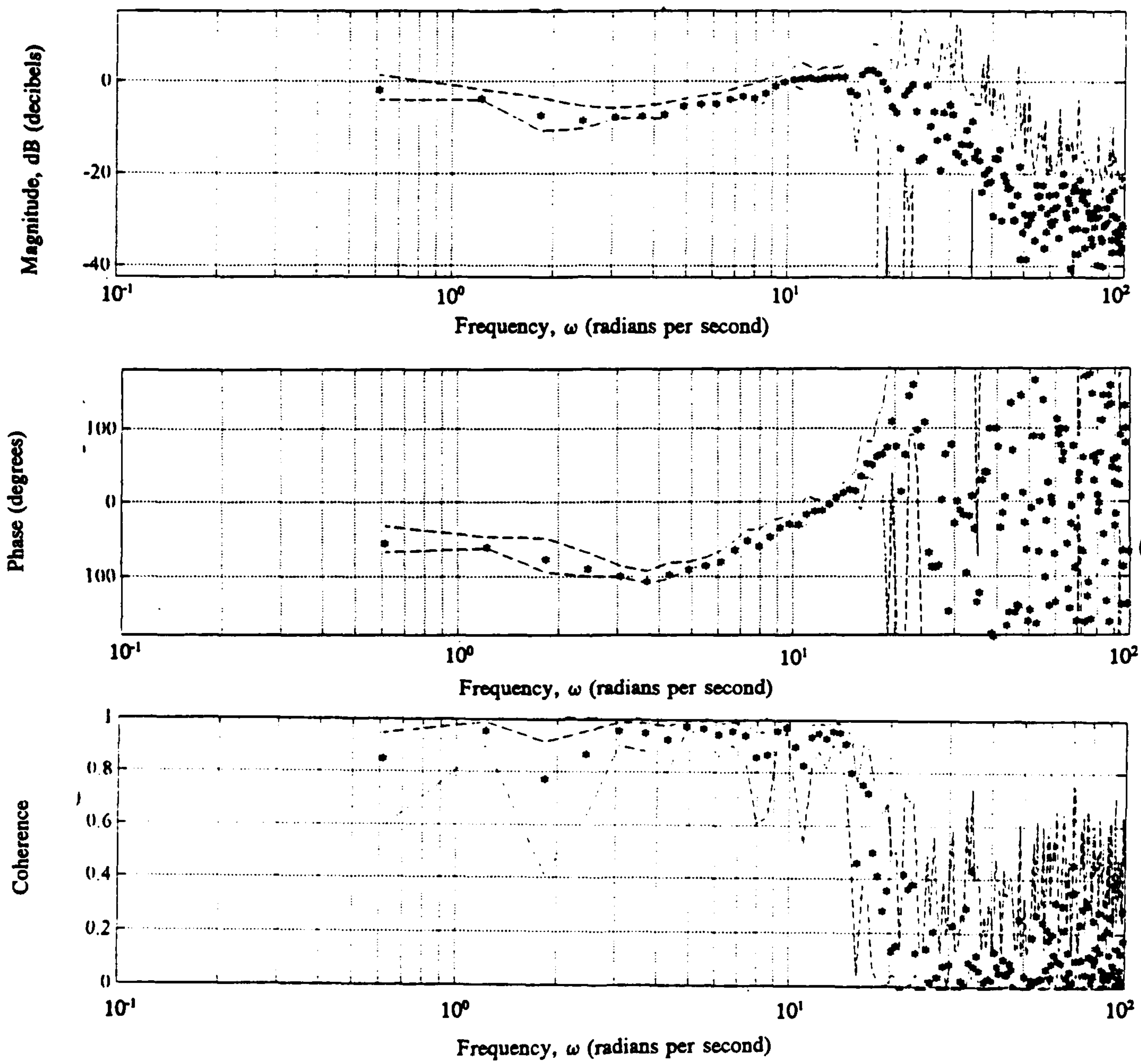
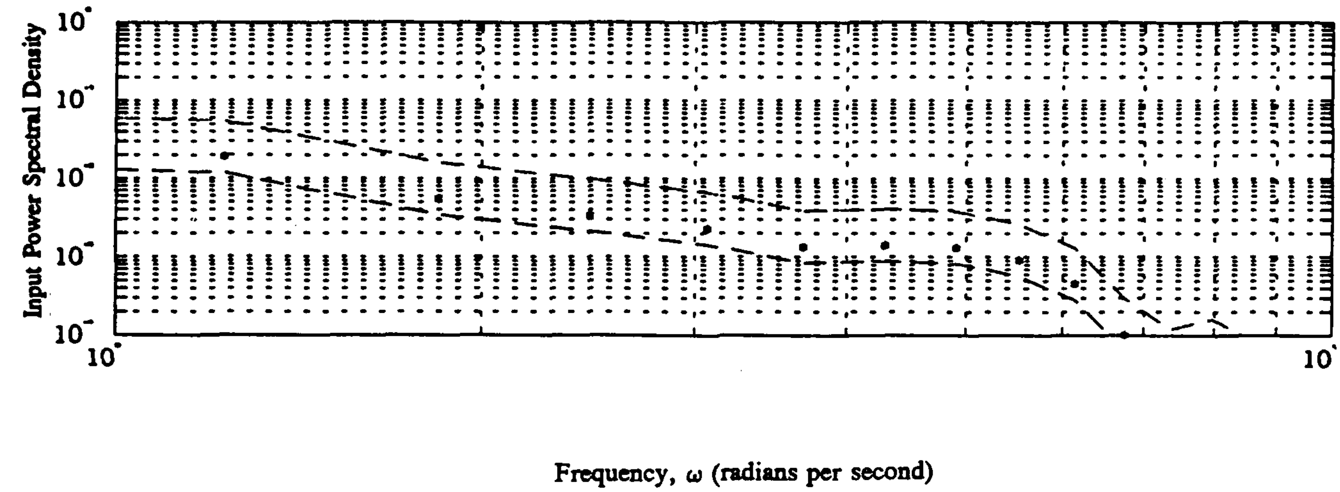


Figure K2: Frequency Response Analysis -
Longitudinal Stick Deflection to Task Error (File F1XS_S_2)

Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 10 Oct 93; Pilot: S; Sortie #2
Sum-of-Sines Tracking Task; Case 1 (See Appendix D)
Airborne Data



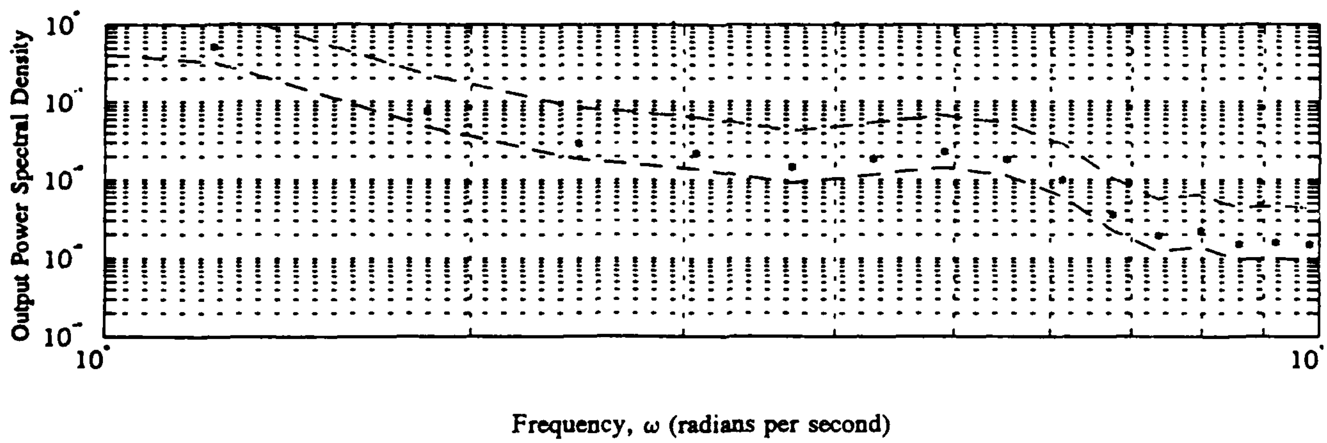


Figure K3: Power Spectral Density -
Longitudinal Stick Force to Task Error (File F1XS_S_2)

Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 10 Oct 93; Pilot: G; Sortie #1
Sum-of-Sines Tracking Task; Case 1 (See Appendix D)
Airborne Data

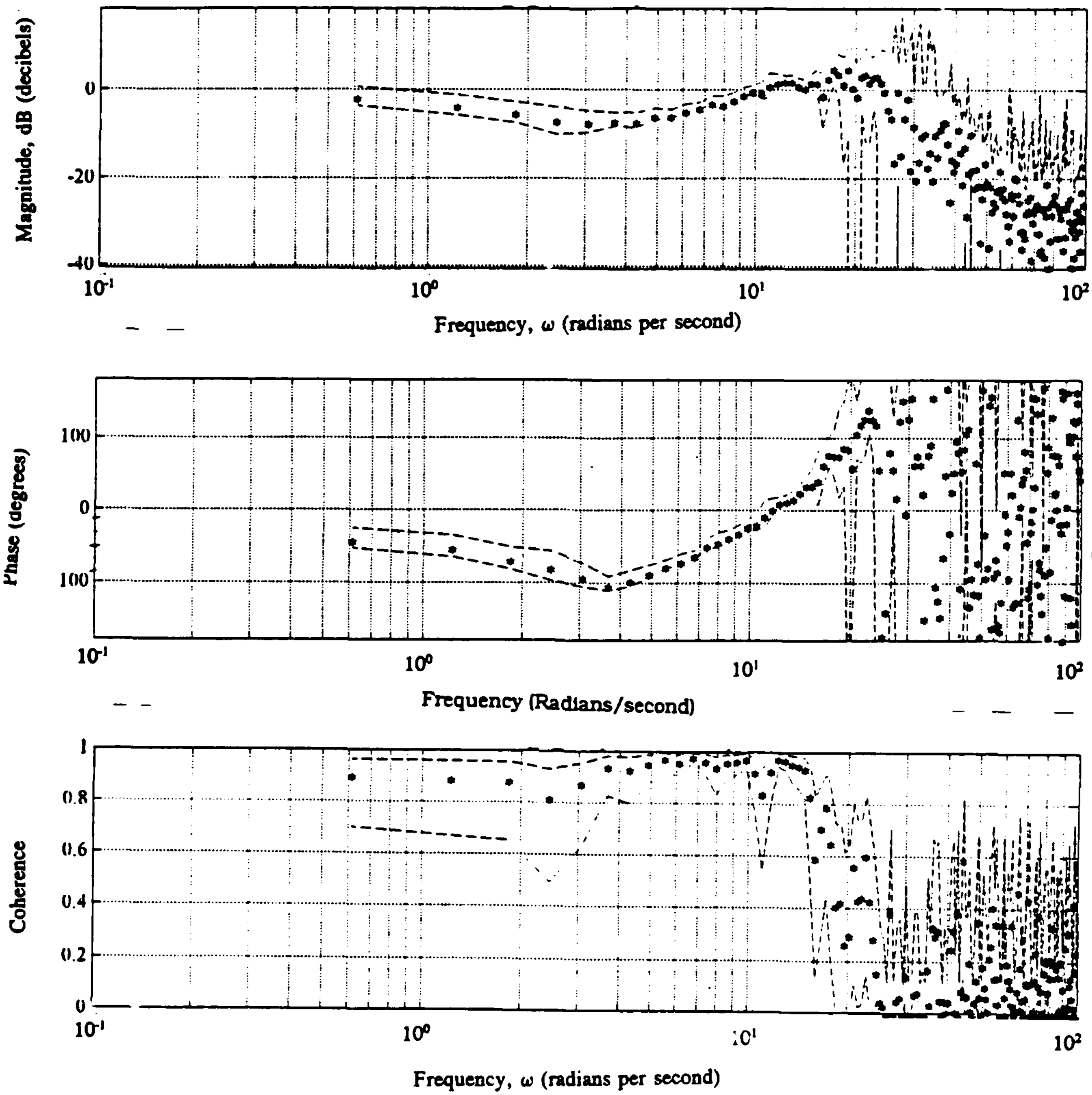


Figure K4: Frequency Response Analysis -
Longitudinal Stick Deflection to Task Error (File F1XS_G_1)

Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 10 Oct 93; Pilot: G; Sortie #1
Sum-of-Sines Tracking Task; Case 1 (See Appendix D)
Airborne Data

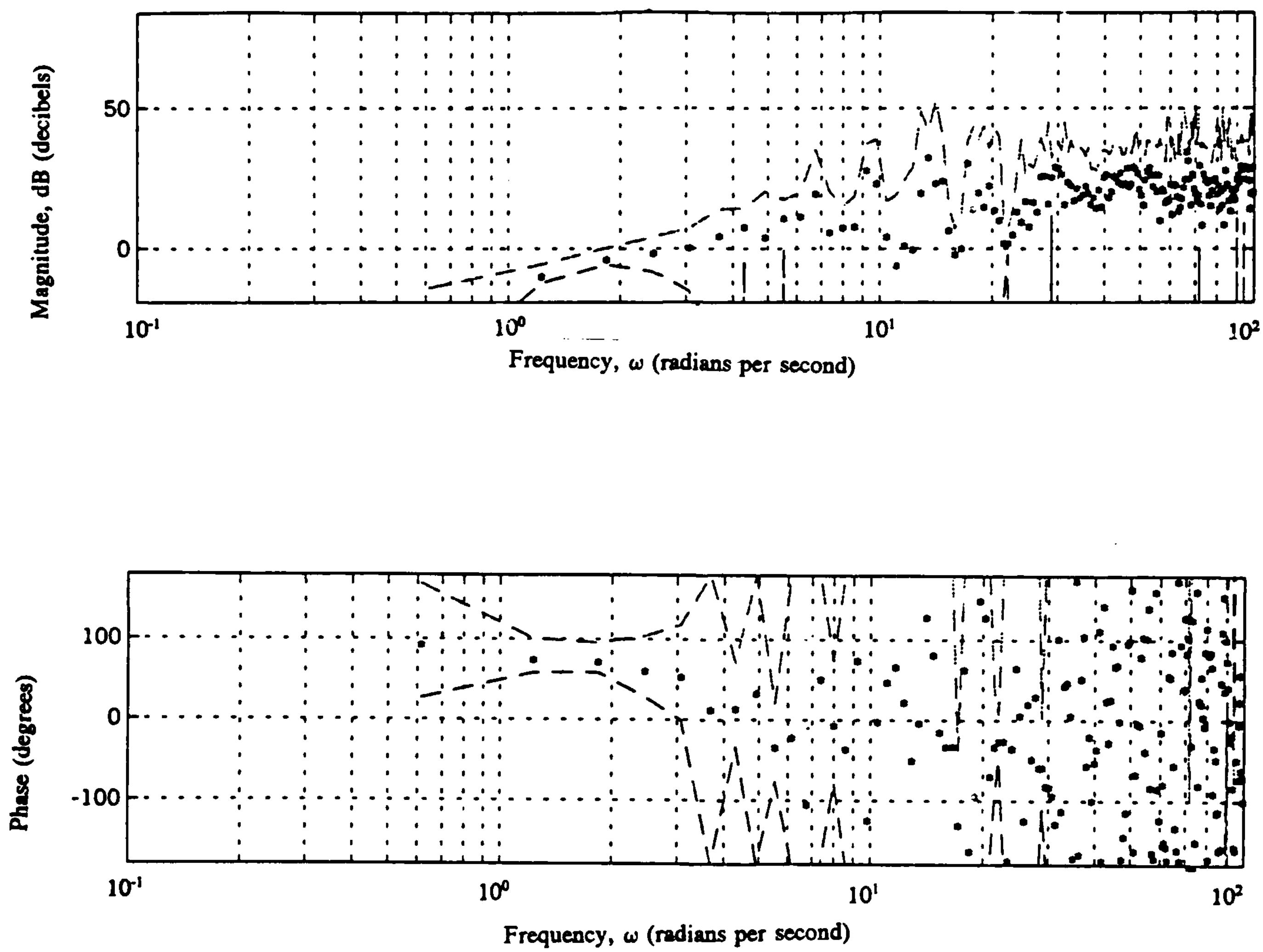
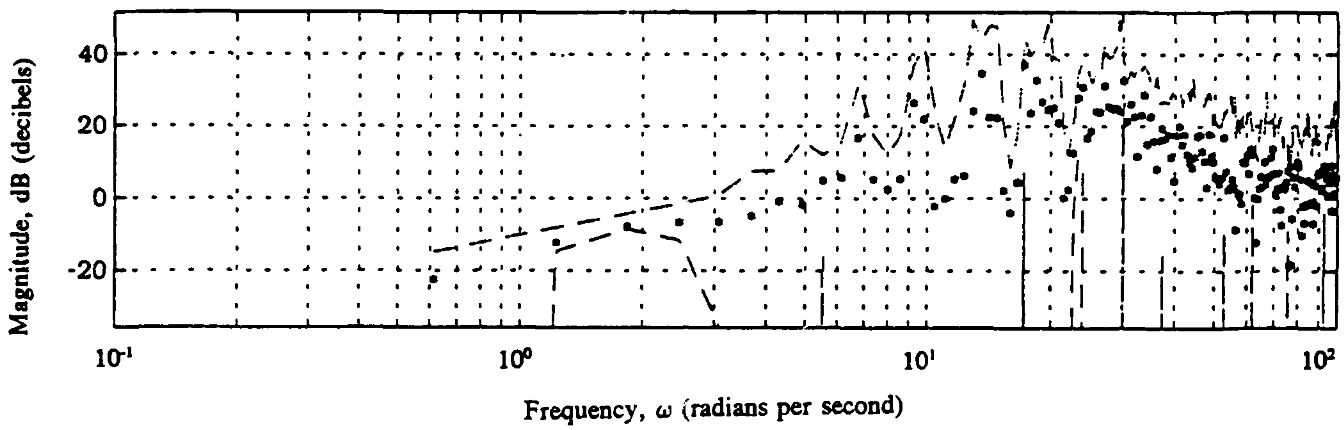


Figure K5: Frequency Response Analysis -
Longitudinal Stick Deflection to Pitch Command (File F1XS_G_1)

Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 10 Oct 93; Pilot: G; Sortie #1
Sum-of-Sines Tracking Task; Case 1 (See Appendix D)
Airborne Data



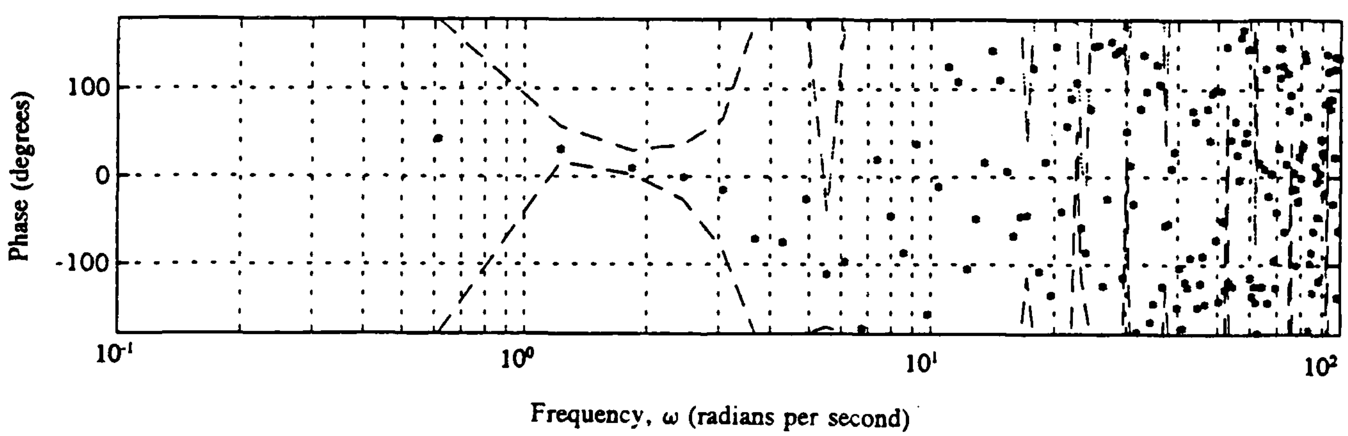


Figure K6: Frequency Response Analysis -
Task Error to Pitch Command (File F1XS_G_1)

Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 10 Oct 93; Pilot: G; Sortie #1
Sum-of-Sines Tracking Task; Case 1 (See Appendix D)
Airborne Data

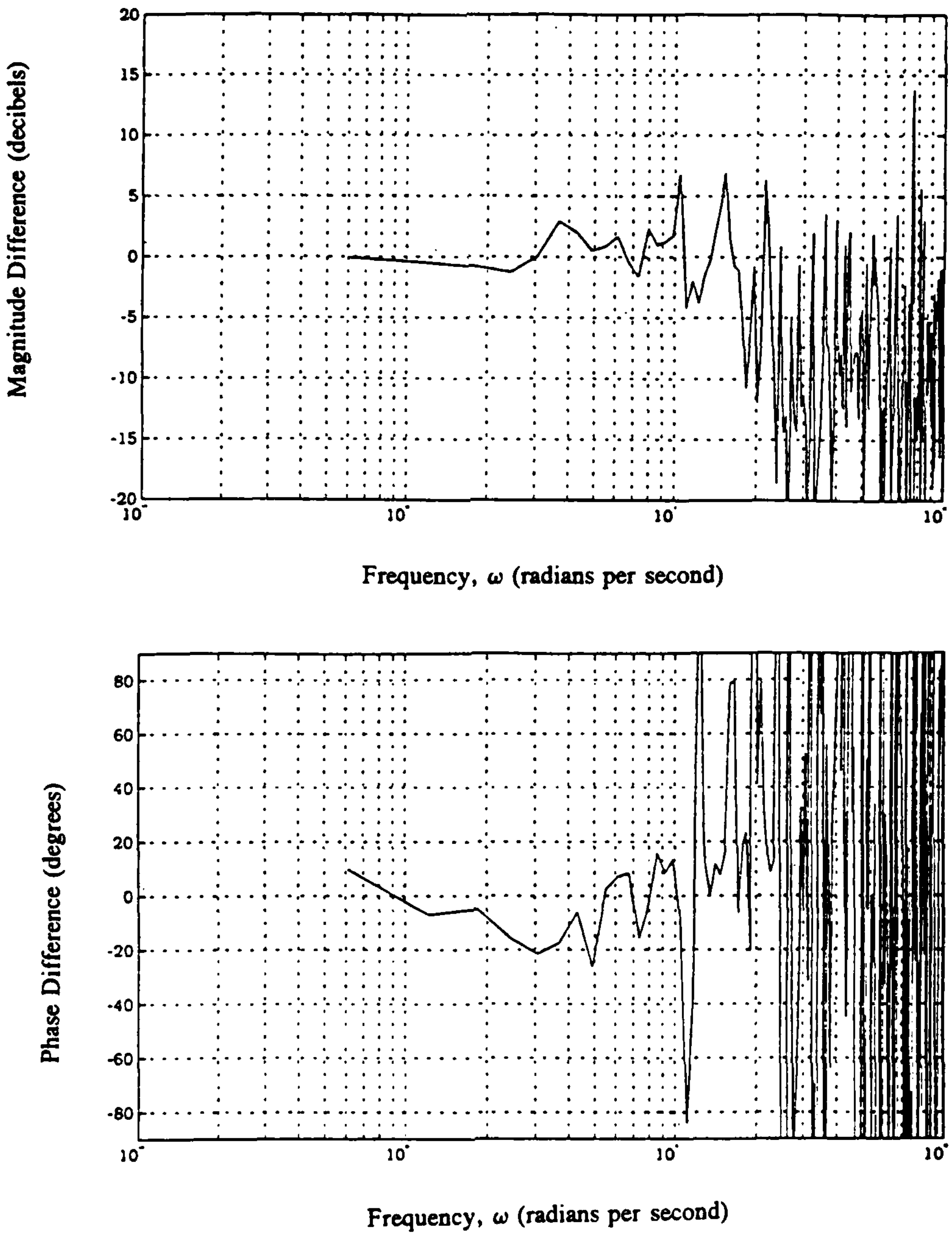


Figure K7: Frequency Response Comparison -
Longitudinal Stick Deflection to Task Error (File F1XS_G_1)

Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 11 Oct 93; Pilot: G; Sortie #5
Sum-of-Sines Tracking Task; Case 1 (See Appendix D)
Airborne Data

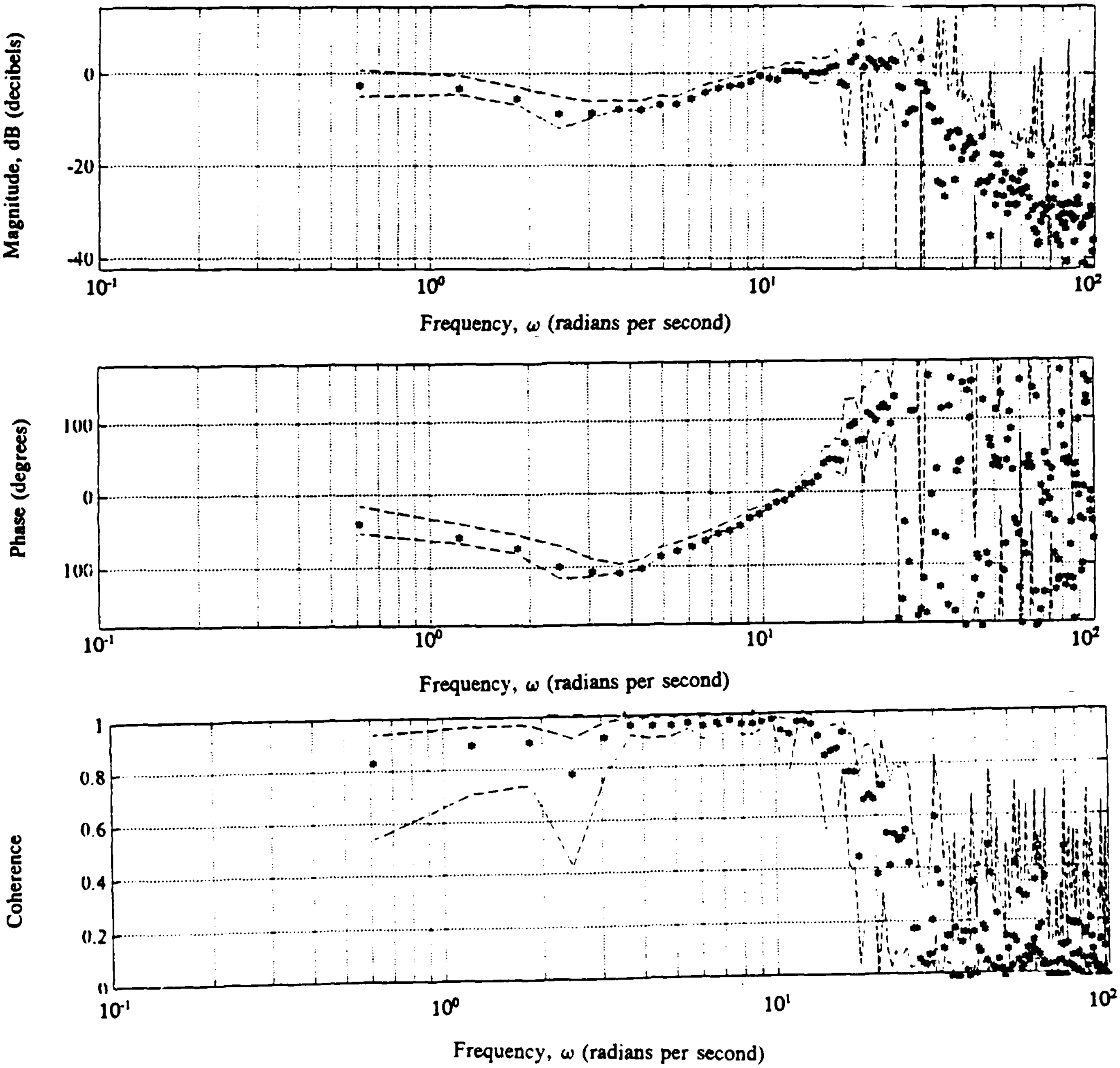


Figure K8: Frequency Response Analysis -
Longitudinal Stick Deflection to Task Error (File F1XS_G_5)

Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 10 Oct 93; Pilot: E; Sortie #2
Sum-of-Sines Tracking Task; Case 4 (See Appendix D)
Airborne Data

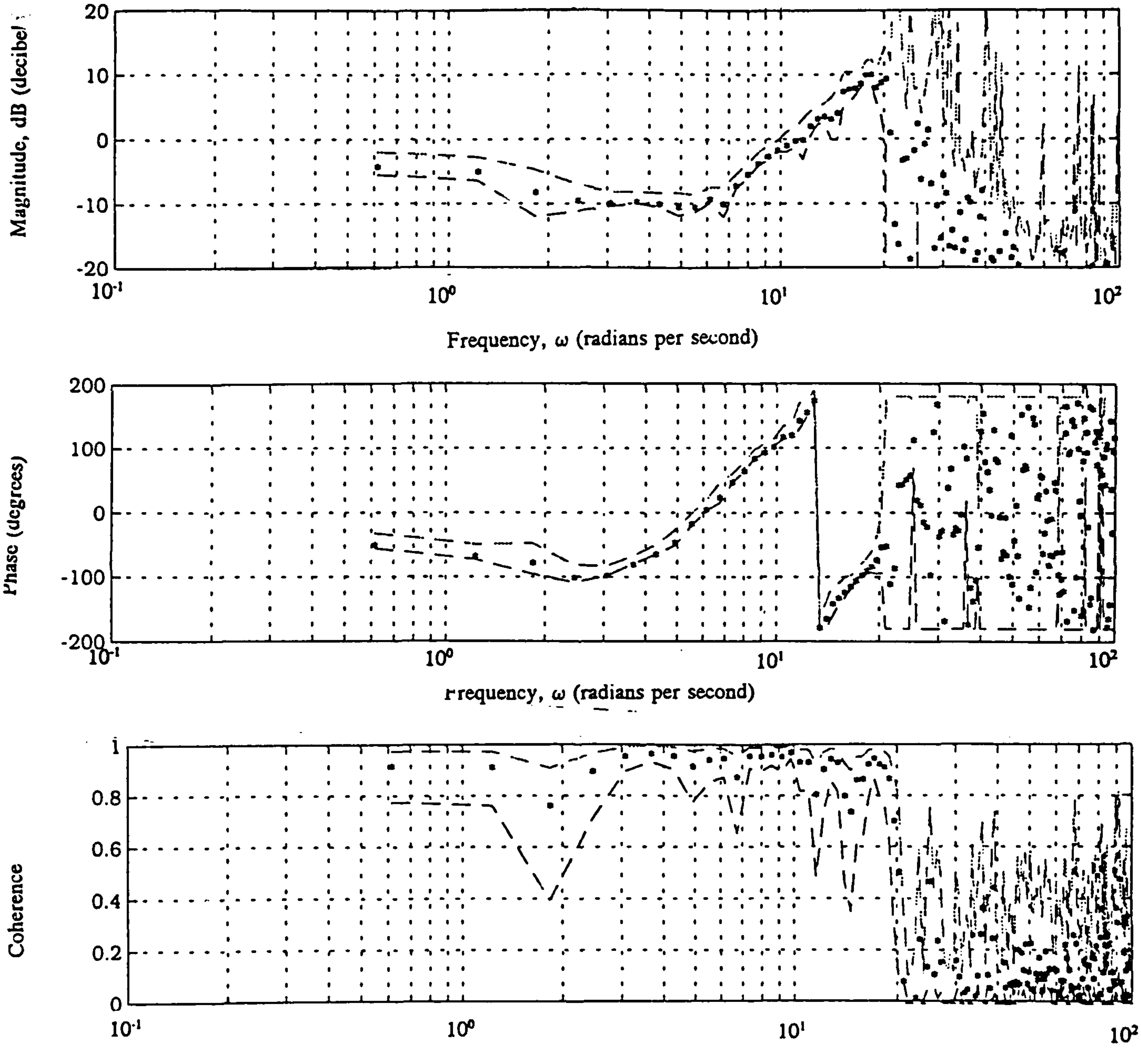
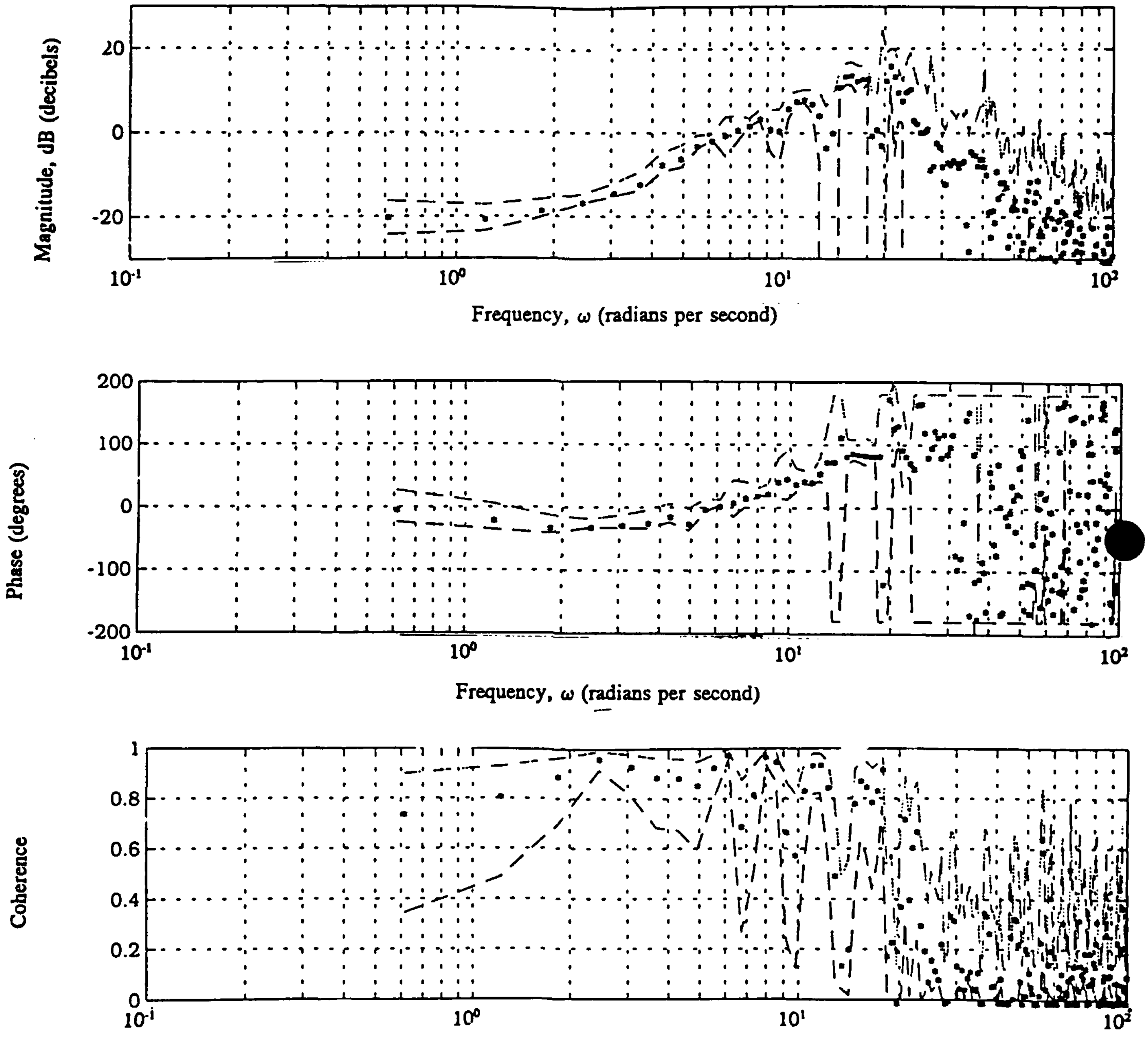


Figure K9: Frequency Response Analysis -
Longitudinal Stick Deflection to Task Error (File F4XS_E_2)

Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 10 Oct 93; Pilot: G; Sortie #1
Sum-of-Sines Tracking Task; Case A (See Appendix D)
Airborne Data



Frequency, ω (radians per second)

Figure K10: Frequency Response Analysis -
Lateral Stick Deflection to Task Error (File FXAS_G_1)

Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 10 Oct 93; Pilot: E; Sortie #1
Sum-of-Sines Tracking Task; Case D (See Appendix D)
Airborne Data

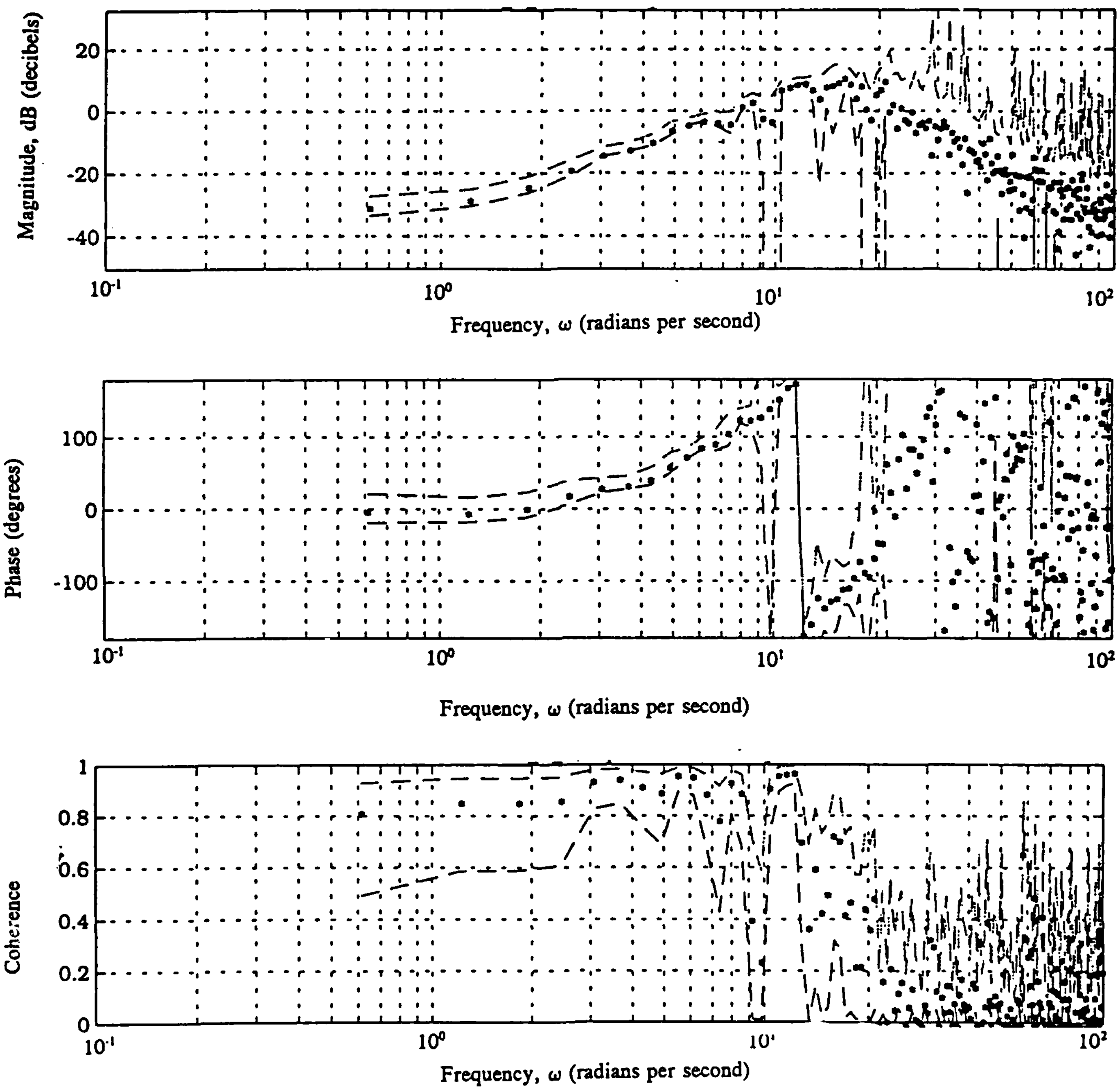


Figure K11: Frequency Response Analysis -
Lateral Stick Deflection to Task Error (File FXDS_E_1)

Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 11 Oct 93; Pilot: G; Sortie #5
Sum-of-Sines Tracking Task; Case 1 (See Appendix D)
Airborne Data

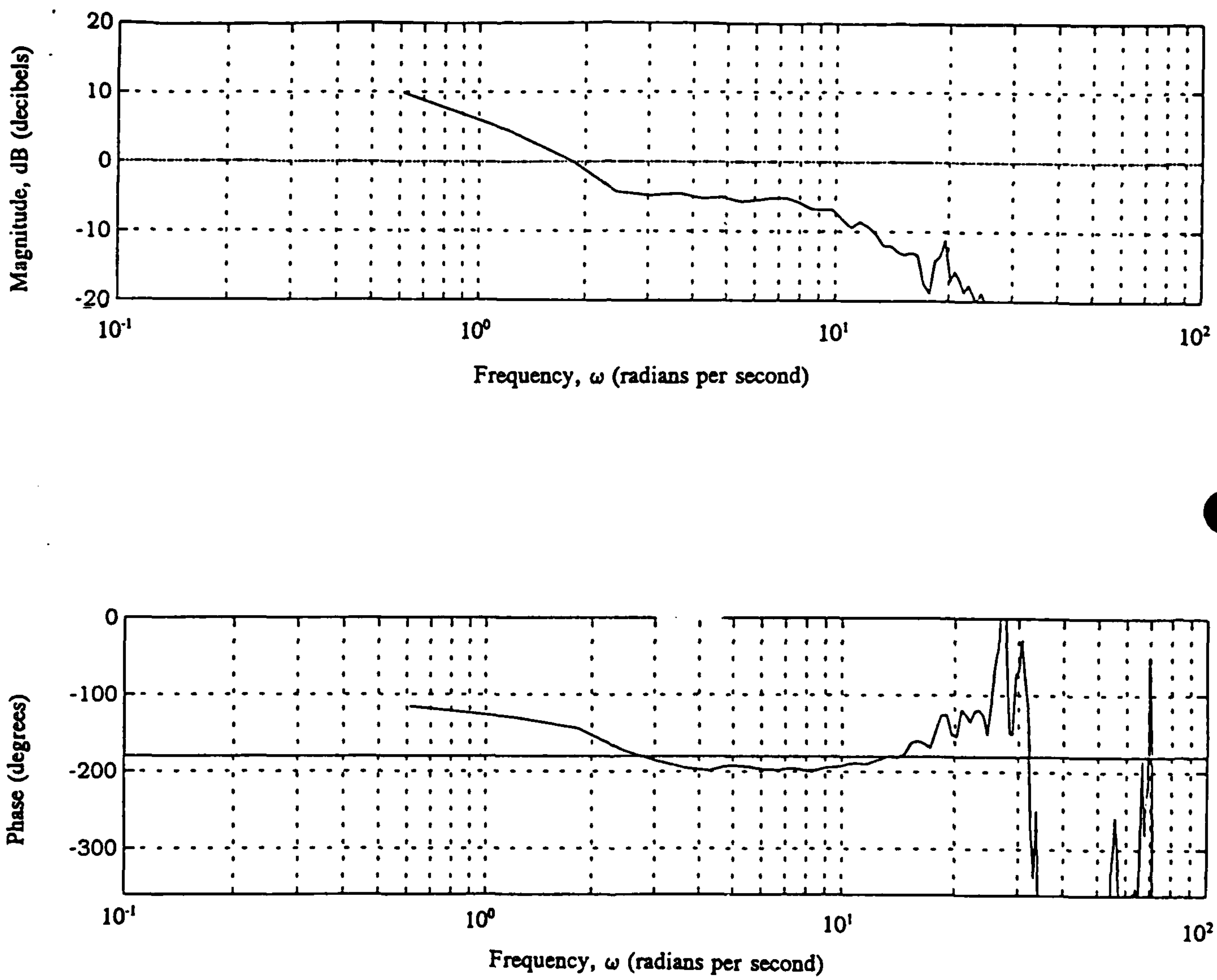


Figure K12: Combined Pilot-Aircraft System - File F1XS_G_5

Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 10 Oct 93; Pilot: E; Sortie #2
Sum-of-Sines Tracking Task; Case 4 (See Appendix D)
Airborne Data

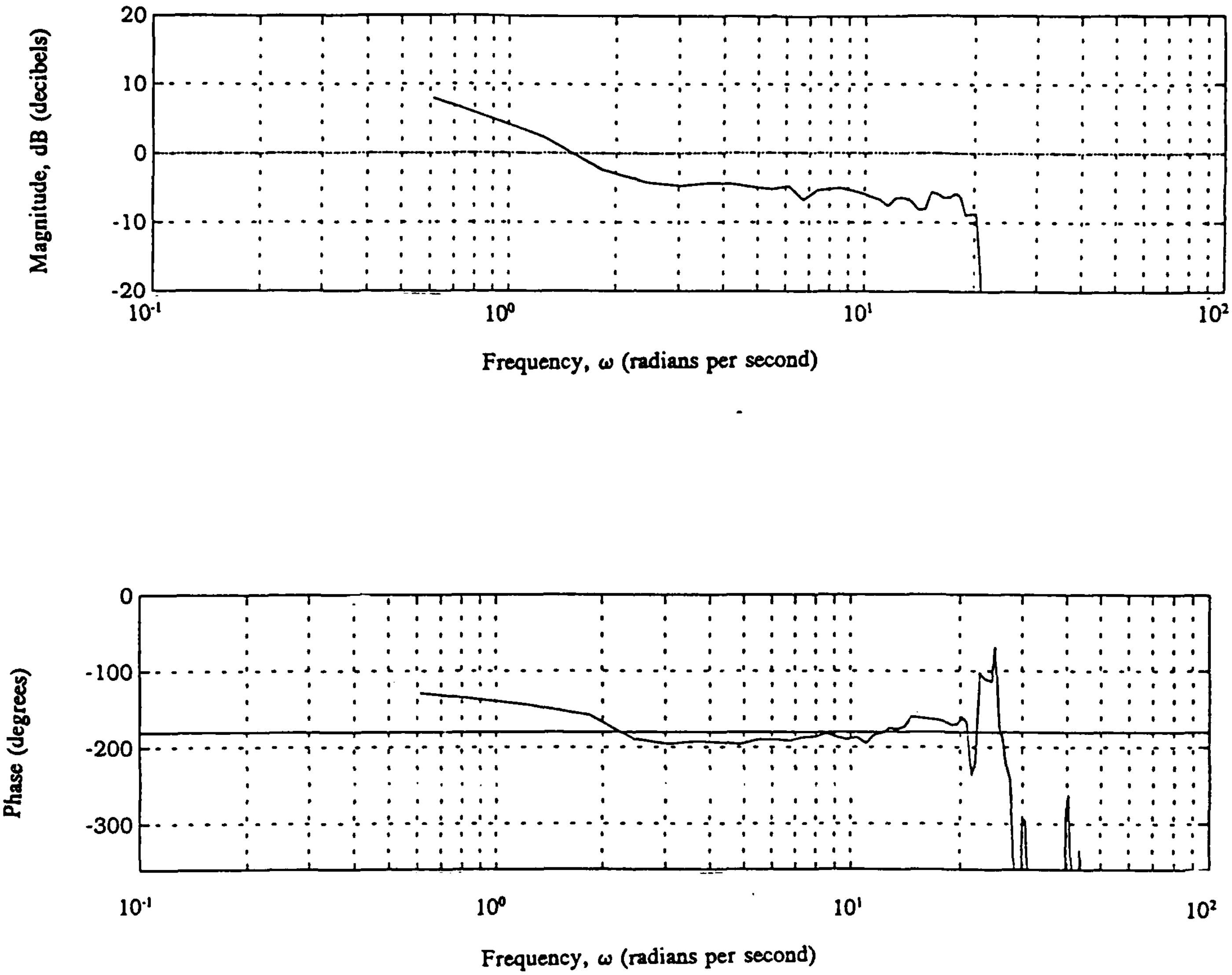


Figure K13: Combined Pilot-Aircraft System - File F4XS_E_2

Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 10 Oct 93; Pilot: G; Sortie #1
Sum-of-Sines Tracking Task; Case A (See Appendix D)
Airborne Data

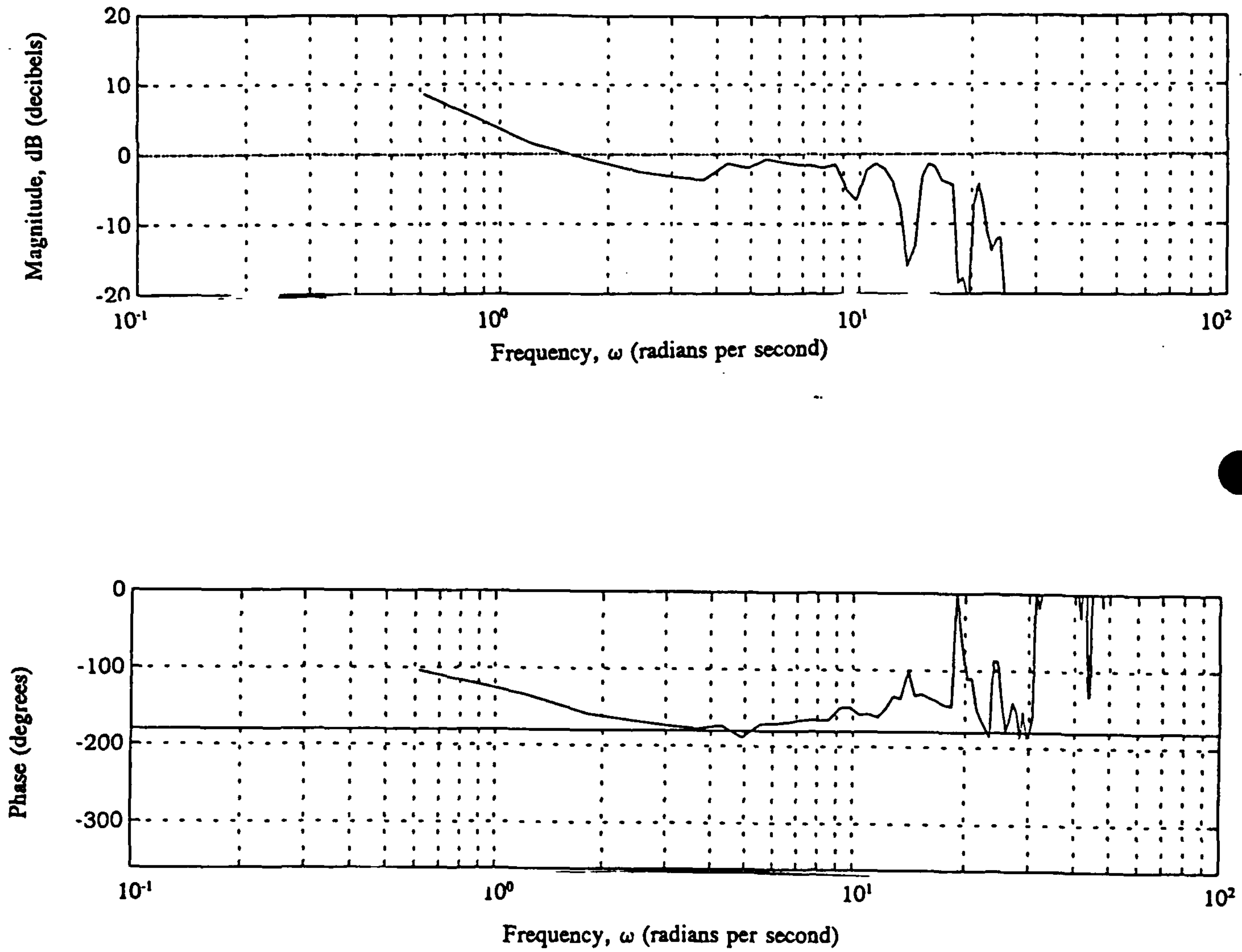


Figure K14: Combined Pilot-Aircraft System - File FXAS_G_1

Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 10 Oct 93; Pilot: E; Sortie #1
Sum-of-Sines Tracking Task; Case D (See Appendix D)
Airborne Data

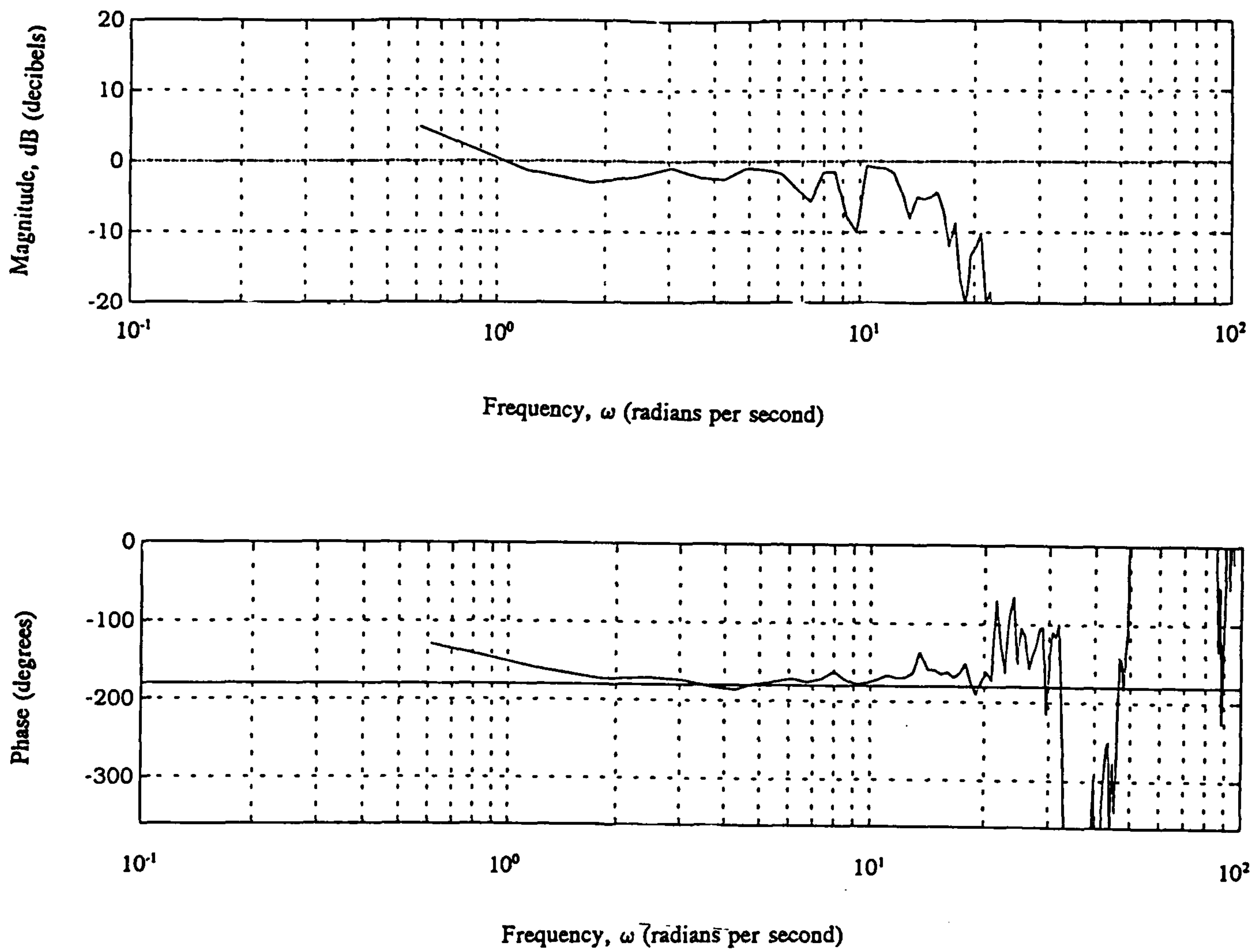


Figure K15: Combined Pilot-Aircraft System - File FXDS_E_1

Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 10 Oct 93; Pilot: G; Sortie #1
Sum-of-Sines Tracking Task; Case 1 (See Appendix D)
Airborne Data

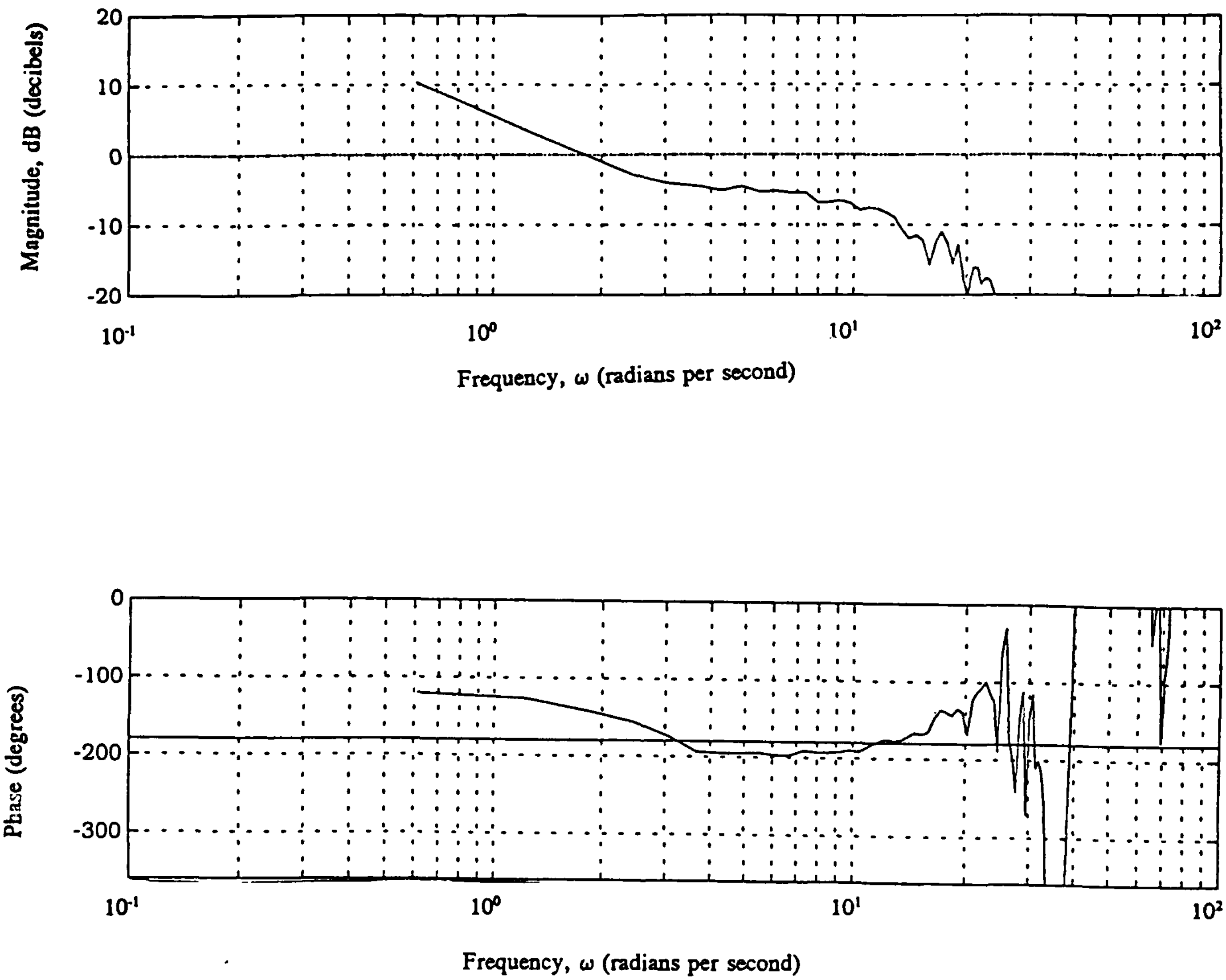
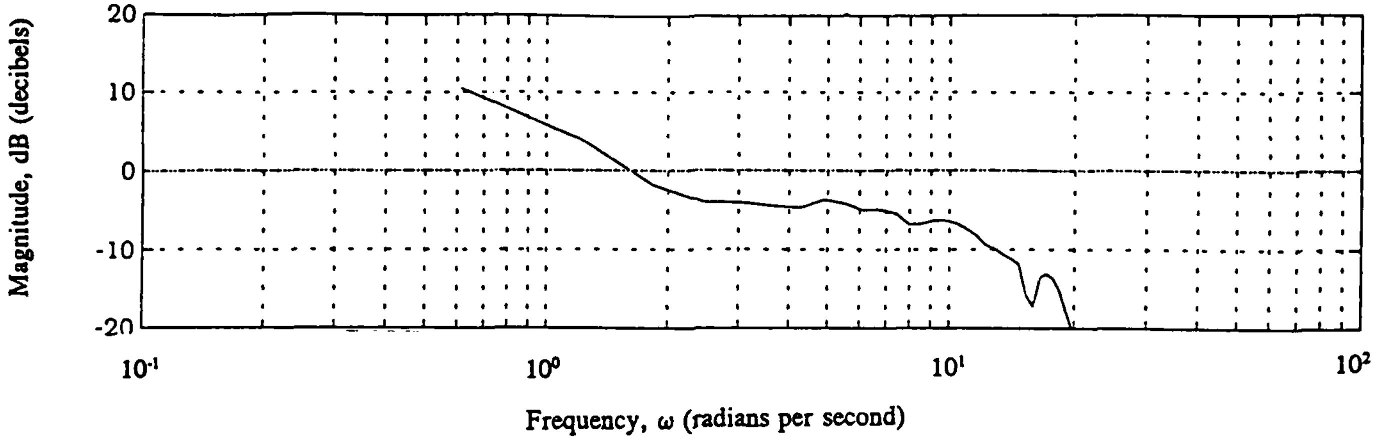


Figure K16: Combined Pilot-Aircraft System - File F1XS_G_1

Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 10 Oct 93; Pilot: S; Sortie #2
Sum-of-Sines Tracking Task; Case 1 (See Appendix D)
Airborne Data



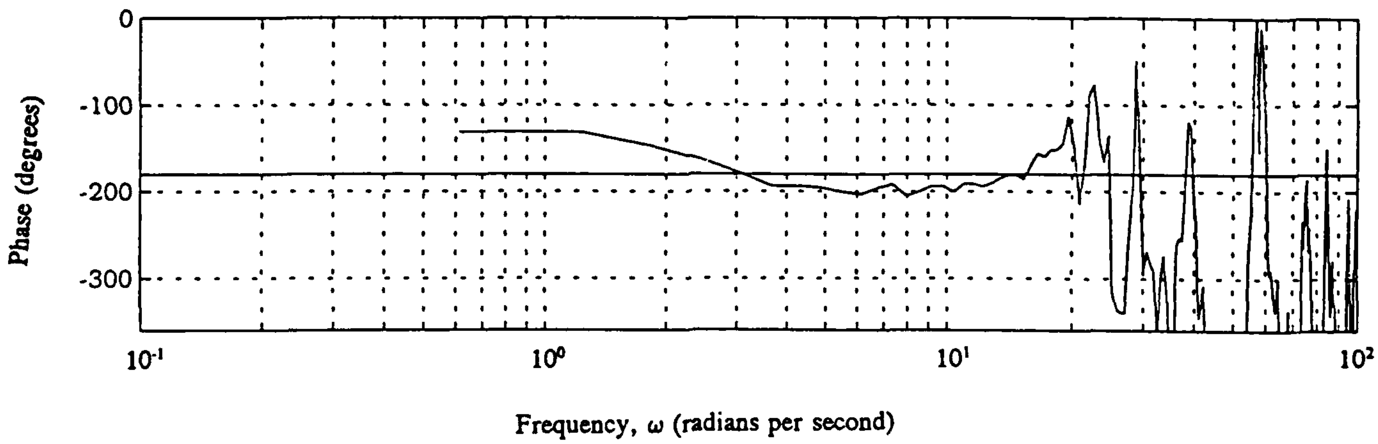
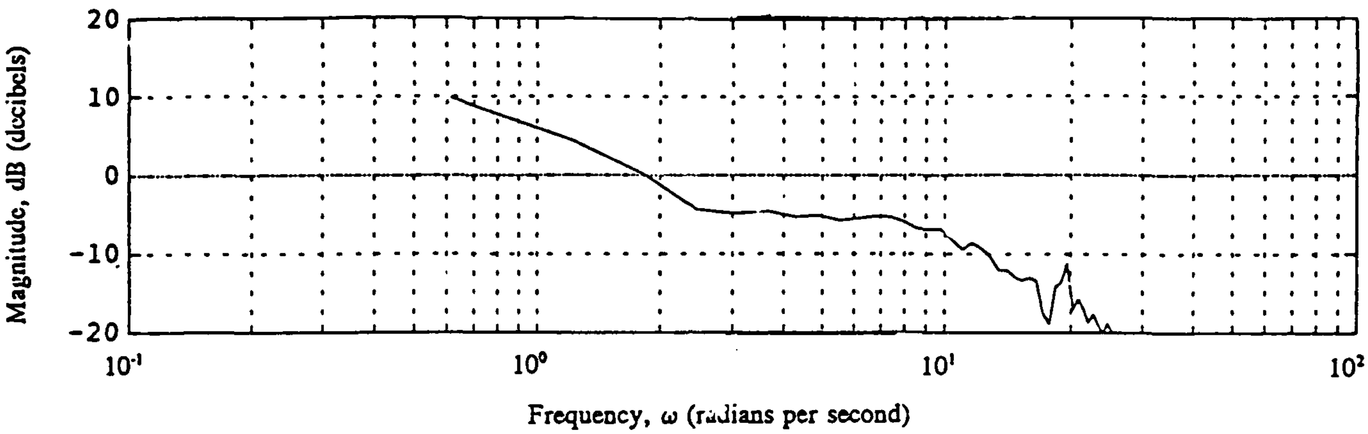


Figure K17: Combined Pilot-Aircraft System - File F1XS_S_2

Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 11 Oct 93; Pilot: G; Sortie #5
Sum-of-Sines Tracking Task; Case 1 (See Appendix D)
Airborne Simulation Data



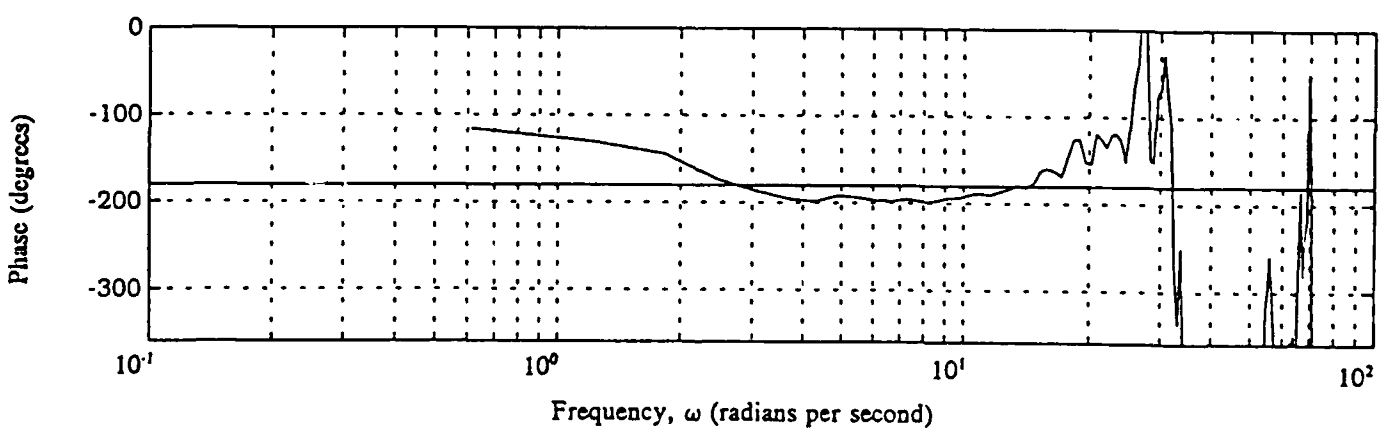


Figure K18: Combined Pilot-Aircraft System - File F1XS_G_5

APPENDIX L

SELECTED NORMAL ACCELERATION FREQUENCY RESPONSE ANALYSIS DATA

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Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 10 Oct 93; Pilot: G; Sortie #1
Sum-of-Sines Tracking Task; Case 1 (See Appendix D)
Airborne Data

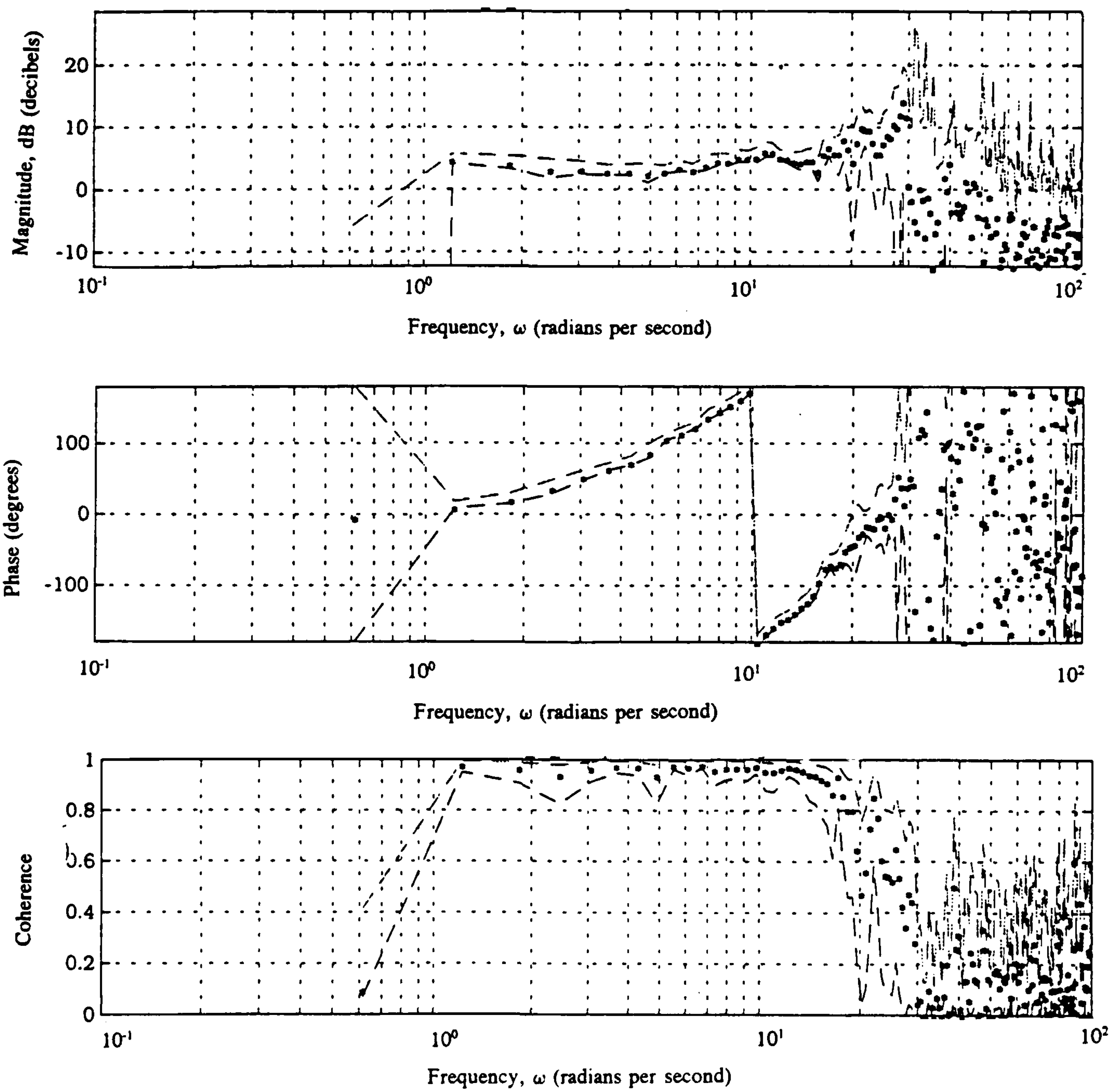

Figure L1: Frequency Response Analysis -
Longitudinal Stick Deflection to Normal Acceleration (File F1XS_G_1)

Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 10 Oct 93; Pilot: G; Sortie #1
Regulator Tracking Task; Case 1 (See Appendix D)
Airborne Data

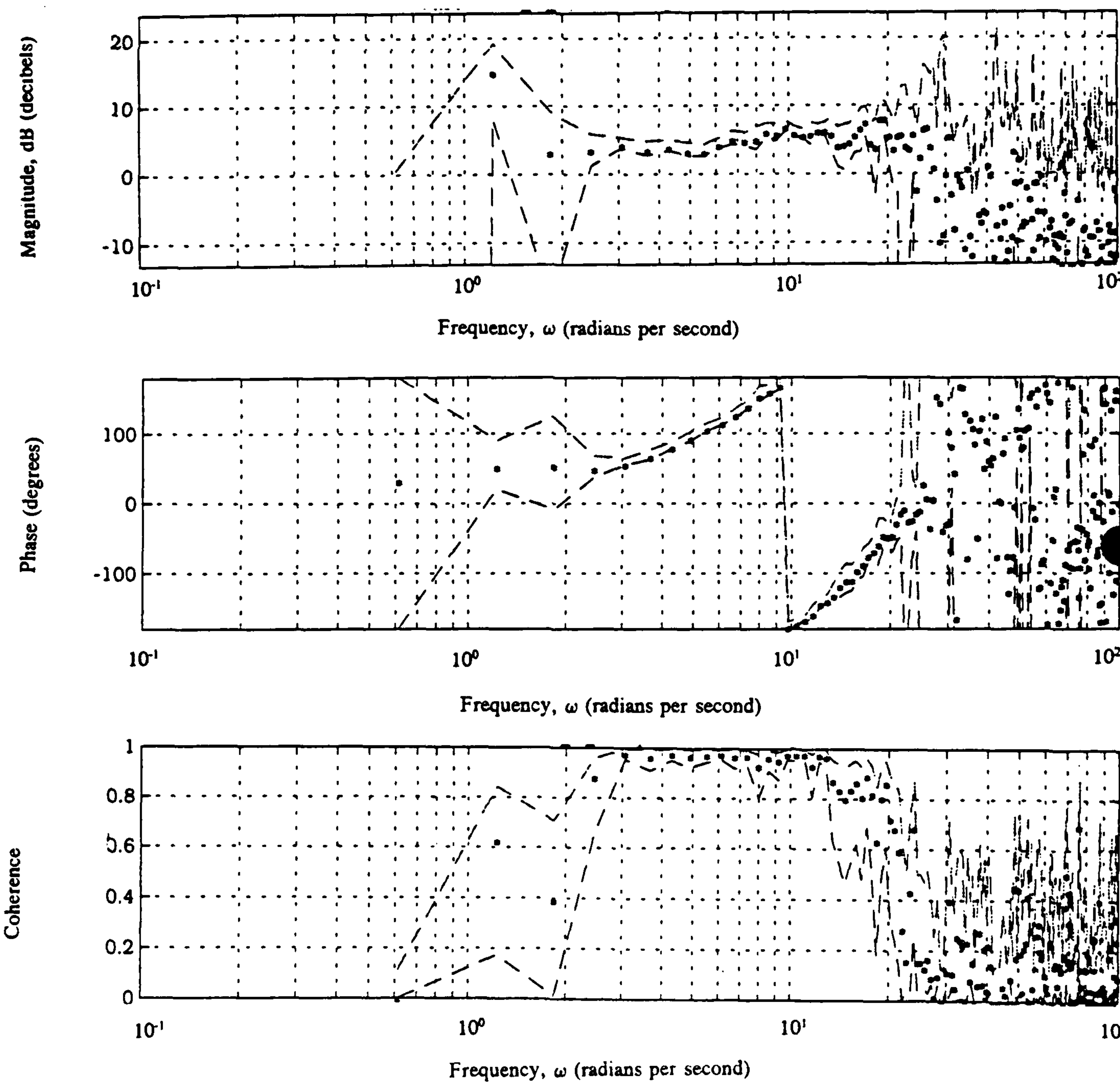

Figure L2: Frequency Response Analysis -
Longitudinal Stick Deflection to Normal Acceleration (File F1XR_G_1)

Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 9 Oct 93; Pilot: S; Sortie #1
Sum-of-Sines Tracking Task; Case 1 (See Appendix D)
Ground Simulation Data

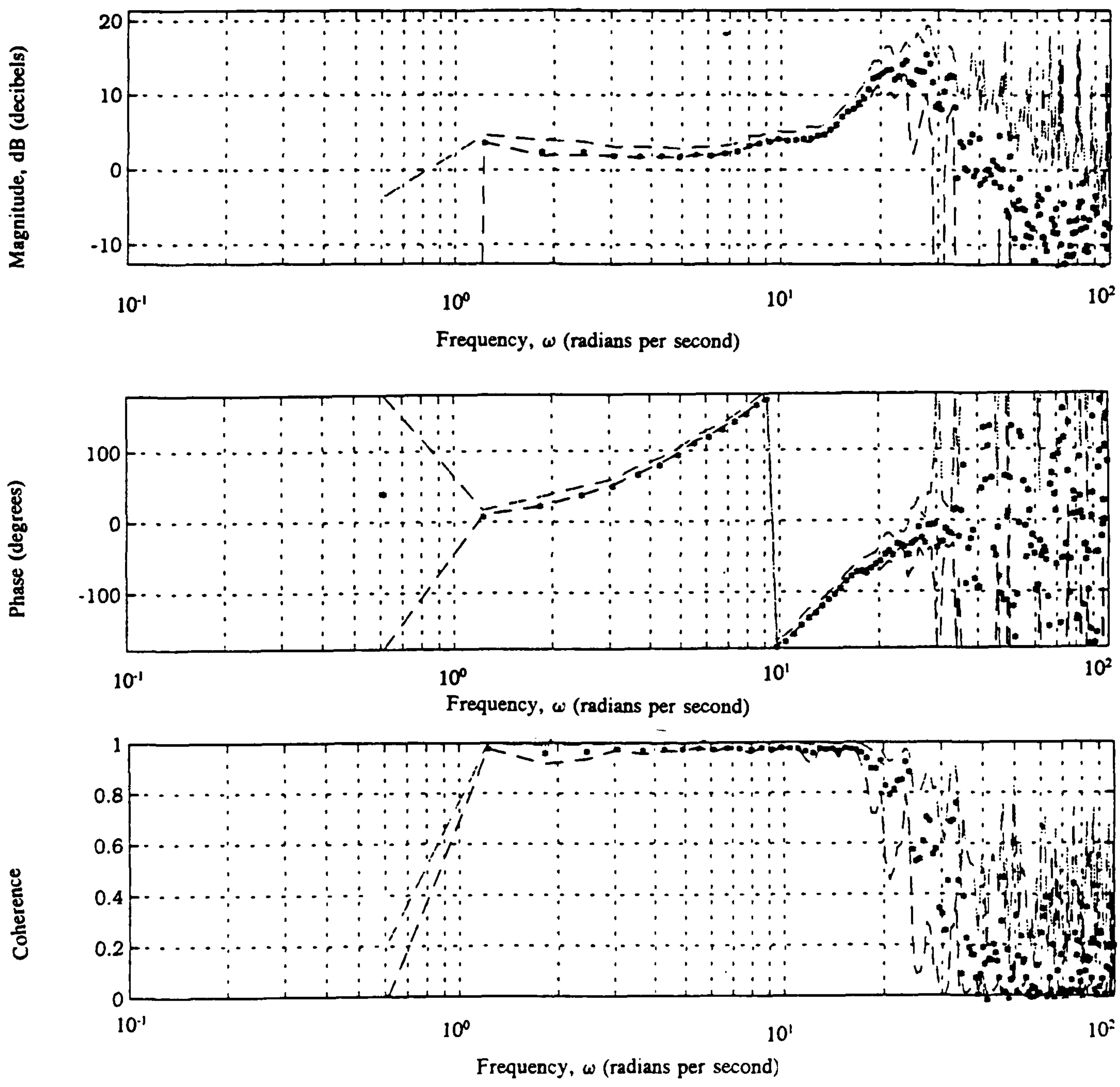

Figure L3: Frequency Response Analysis -
Longitudinal Stick Deflection to Normal Acceleration (File G1XS_S_)

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APPENDIX M

SELECTED PILOT RESPONSE DATA FOR GROUND SIMULATION

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Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 9 Oct 93; Pilot: S; Session #3
Sum-of-Sines Tracking Task; Case 1 (See Appendix D)
Ground Simulation Data

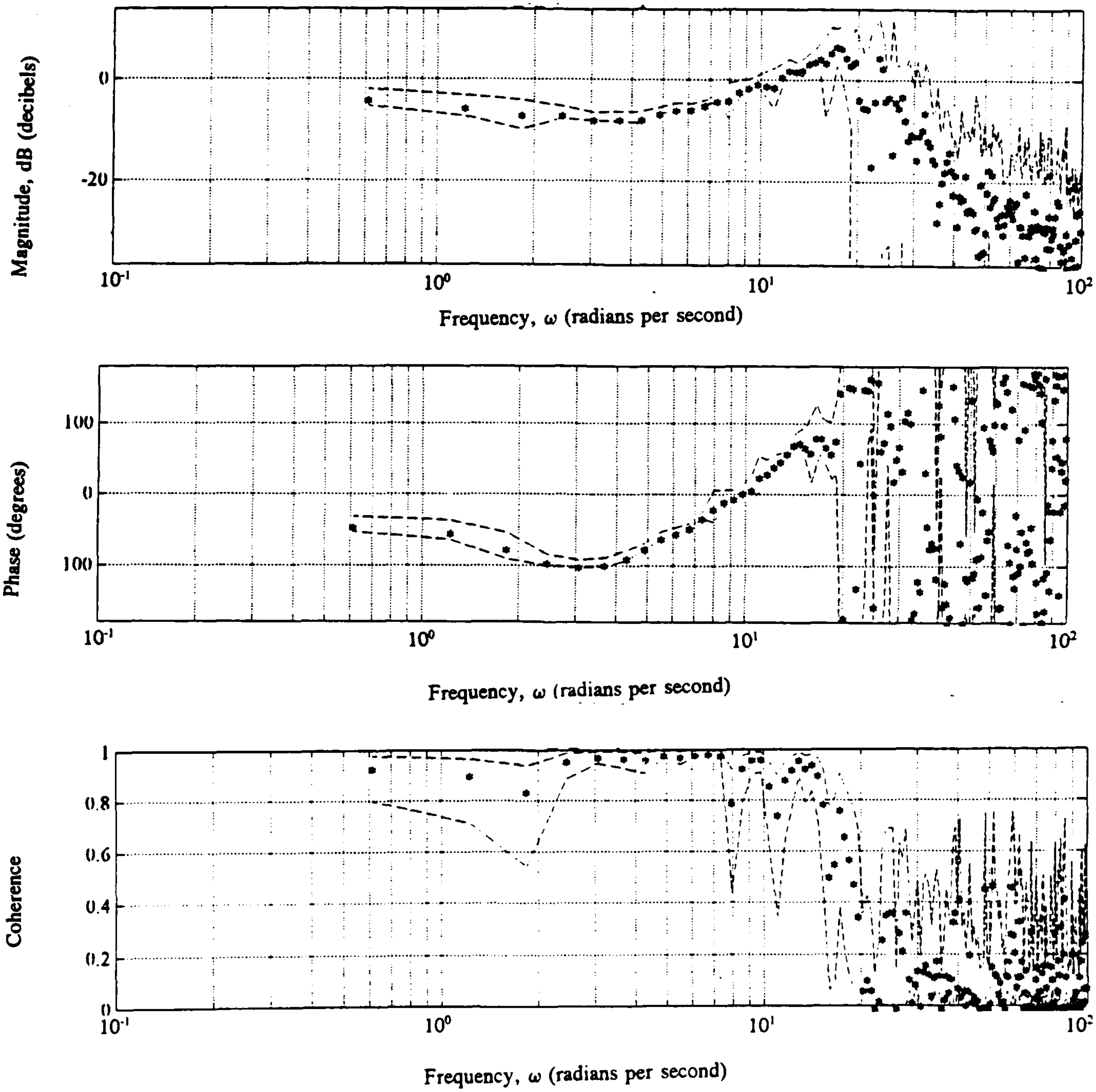

Figure M1: Frequency Response Analysis -
Longitudinal Stick Deflection to Task Error (File G1XS_S_3)

Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 9 Oct 93; Pilot: E; Session #5
Sum-of-Sines Tracking Task; Case 4 (See Appendix D)
Ground Simulation Data

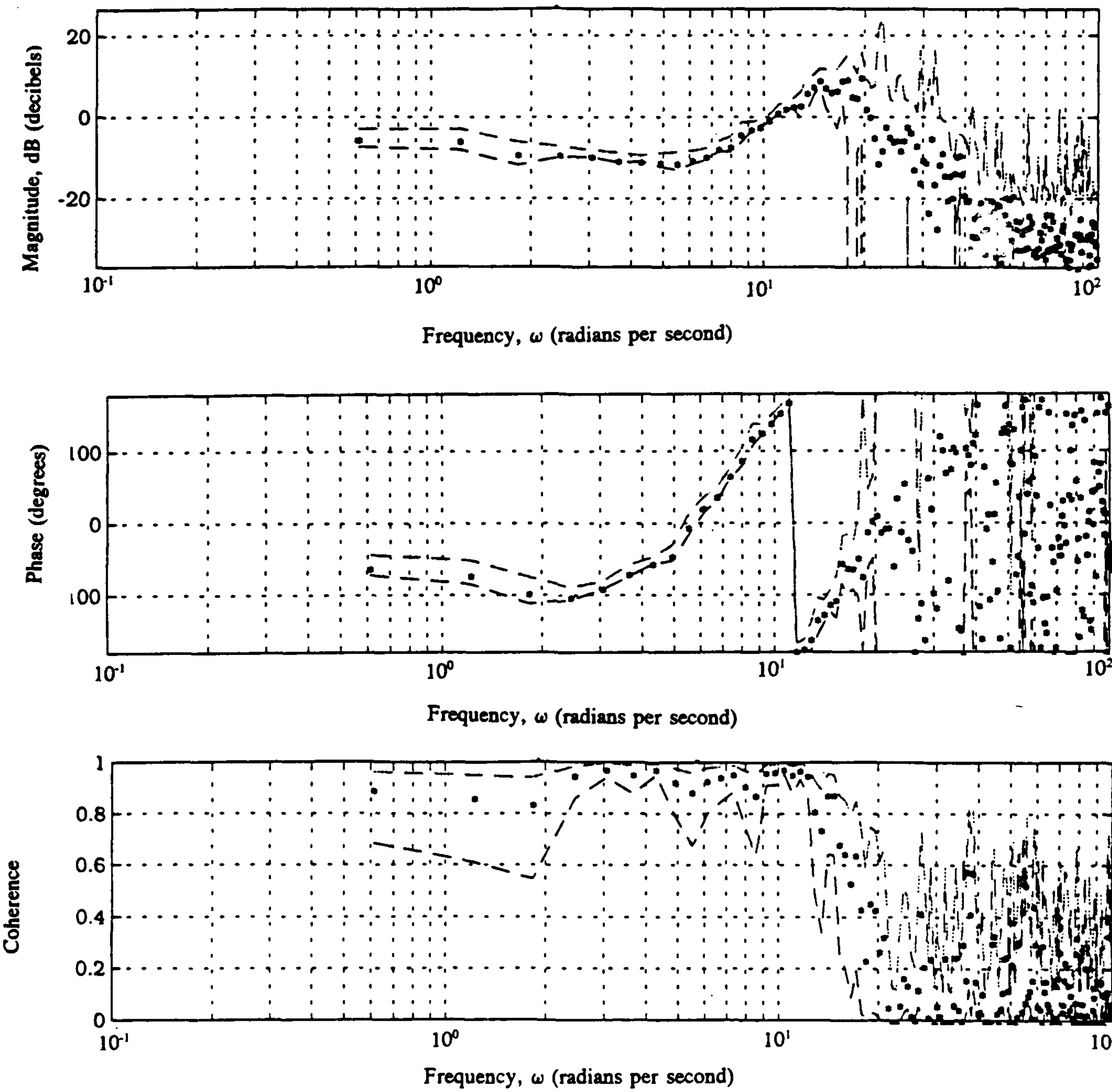

Figure M2: Frequency Response Analysis -
Longitudinal Stick Deflection to Task Error (File G4XS_E_5)

Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 9 Oct 93; Pilot: E; Session #2
Sum-of-Sines Tracking Task; Case A (See Appendix D)
Ground Simulation Data

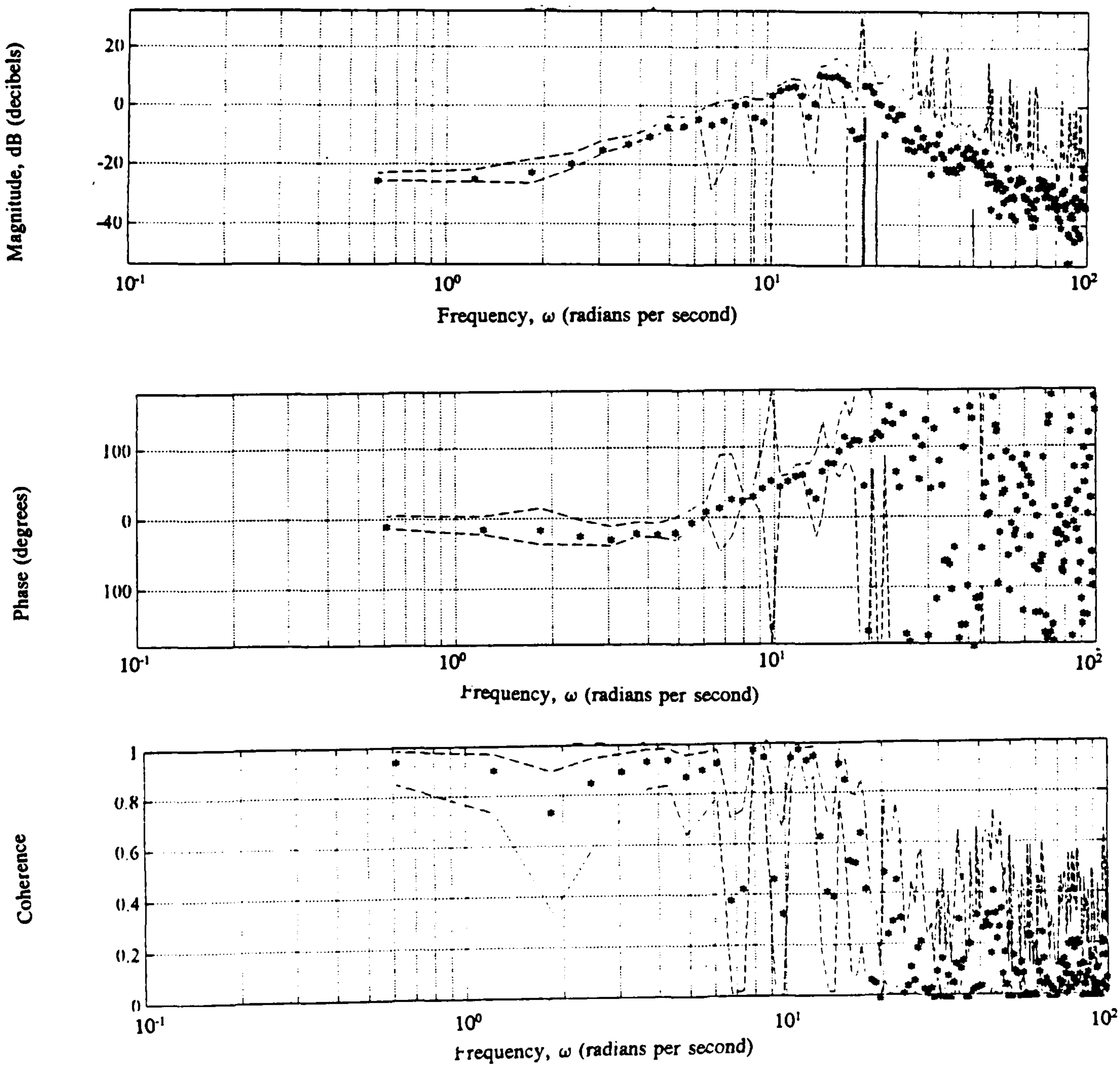

Figure M3: Frequency Response Analysis -
Longitudinal Stick Deflection to Task Error (File GXAS_E_2)

Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 9 Oct 93; Pilot: E; Session #2
Sum-of-Sines Tracking Task; Case D (See Appendix D)
Ground Simulation Data

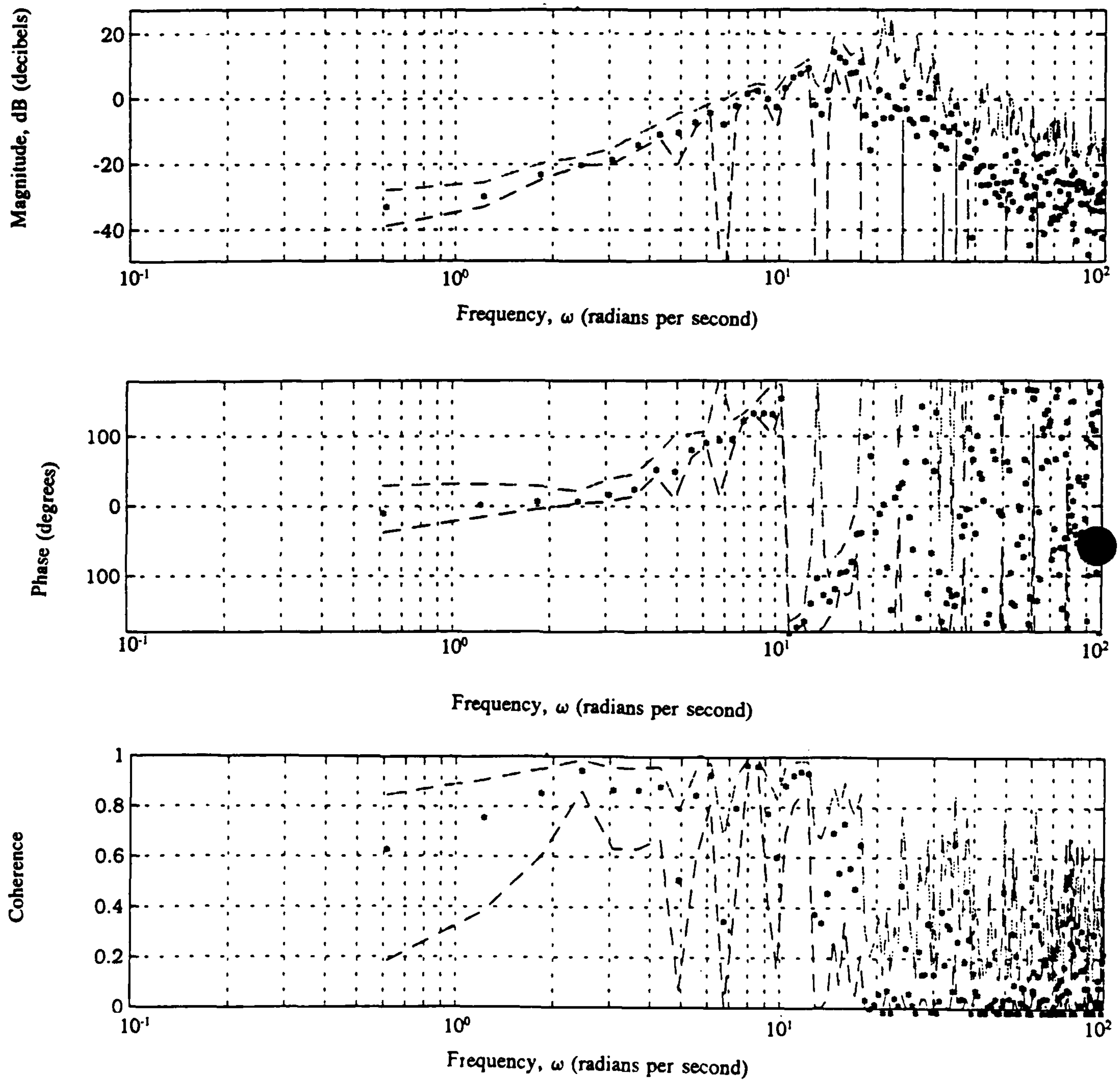

Figure M4: Frequency Response Analysis -
Longitudinal Stick Deflection to Task Error (File GXDS_E_2)

APPENDIX N

SELECTED MULTI-AXIS FREQUENCY RESPONSE ANALYSIS DATA

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Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 10 Oct 93; Pilot: S; Sortie #2
Sum-of-Sines Tracking Task; Case 1A (See Appendix D)
Airborne Data

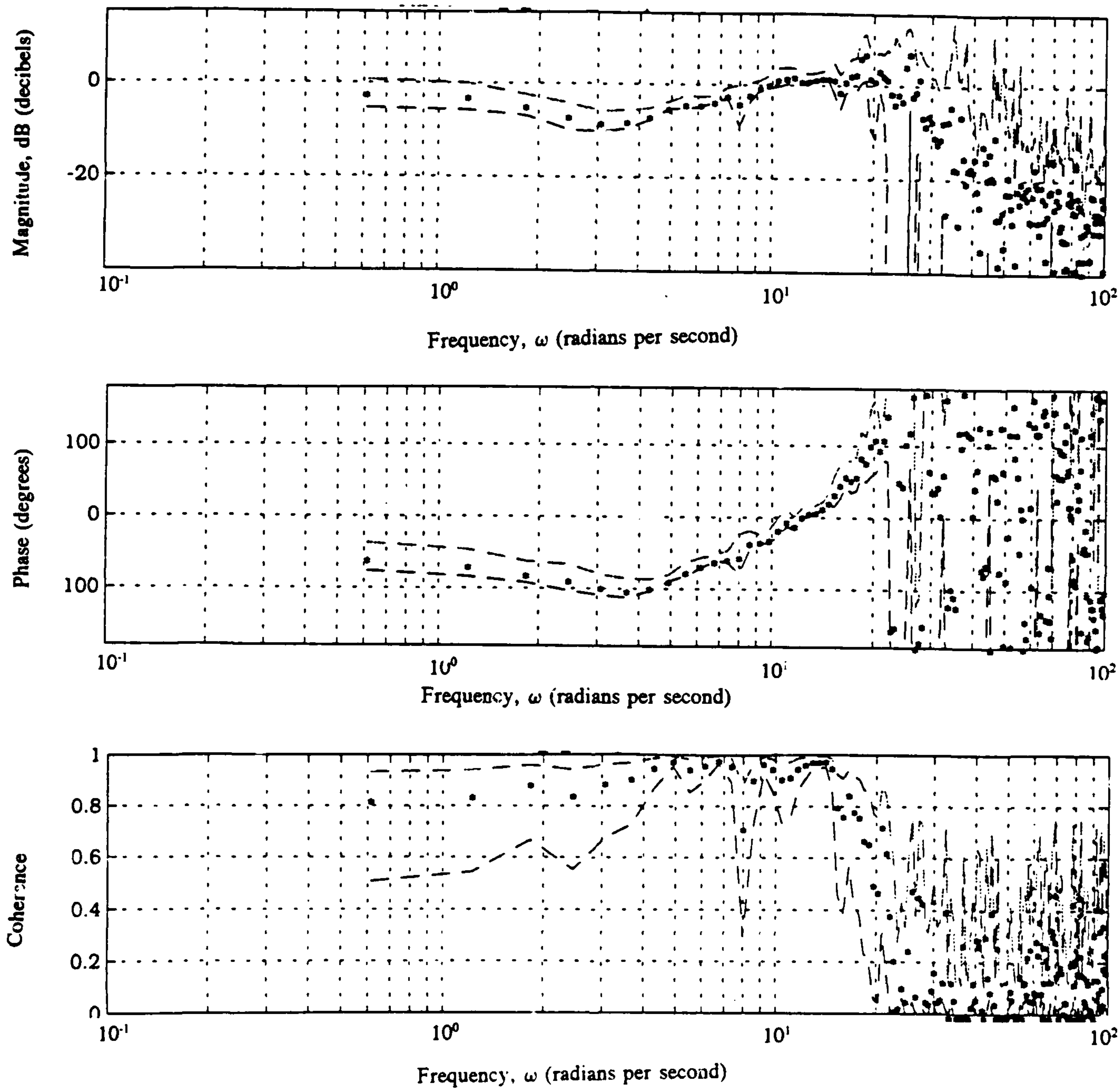

Figure N1: Frequency Response Analysis - Longitudinal Stick Deflection to Task Error (File F1AS_S_2)

Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 10 Oct 93; Pilot: S; Sortie #2
Sum-of-Sines Tracking Task; Case 1A (See Appendix D)
Airborne Data

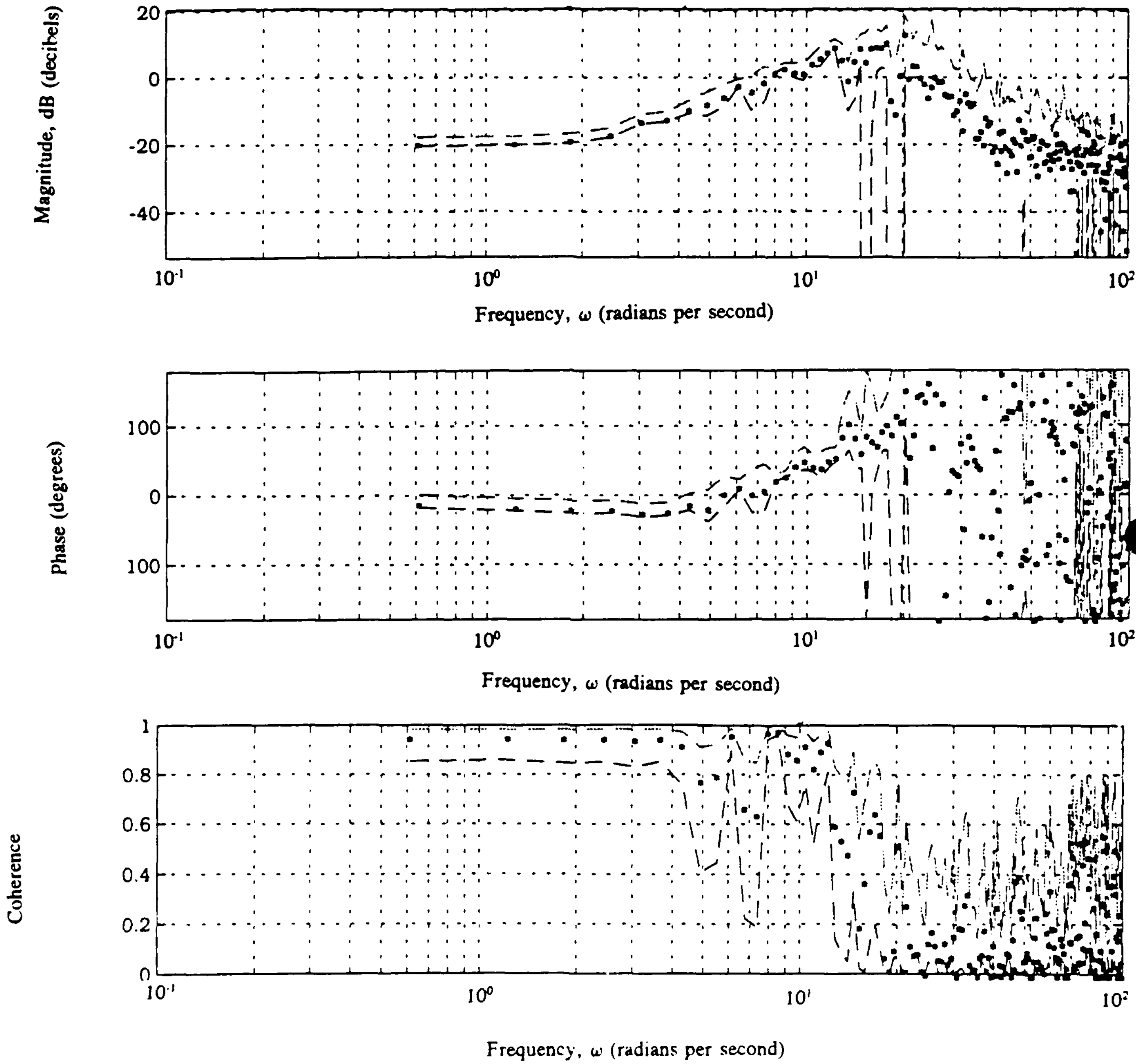

Figure N2: Frequency Response Analysis -
Lateral Stick Deflection to Task Error (File F1AS_S_2)

Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 11 Oct 93; Pilot: G; Sortie #4
Sum-of-Sines Tracking Task; Case 4A (See Appendix D)
Airborne Data

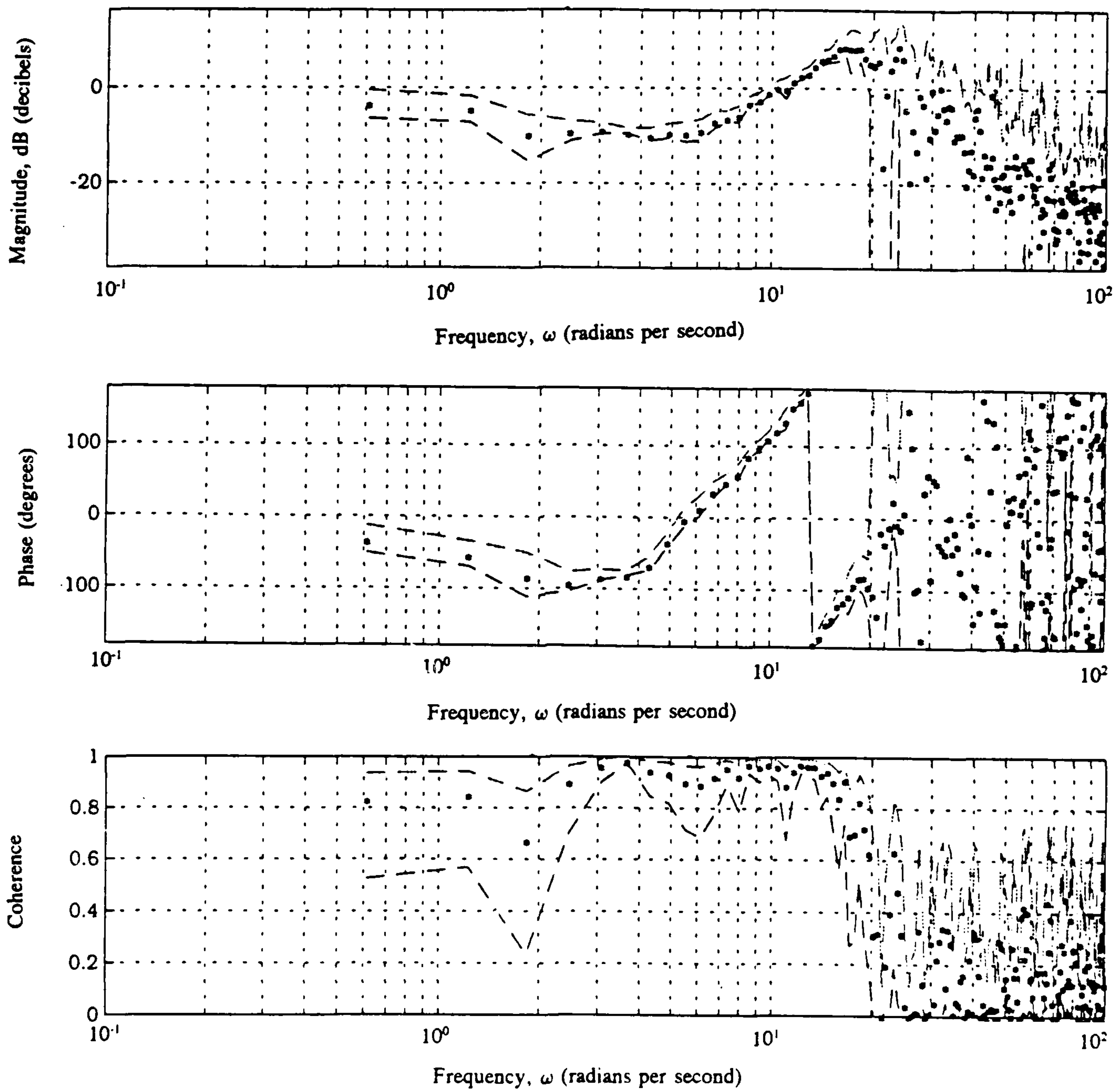

Figure N3: Frequency Response Analysis -
Longitudinal Stick Deflection to Task Error (File F4AS_G_4)

Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 11 Oct 93; Pilot: G; Sortie #4
Sum-of-Sines Tracking Task; Case 4A (See Appendix D)
Airborne Data

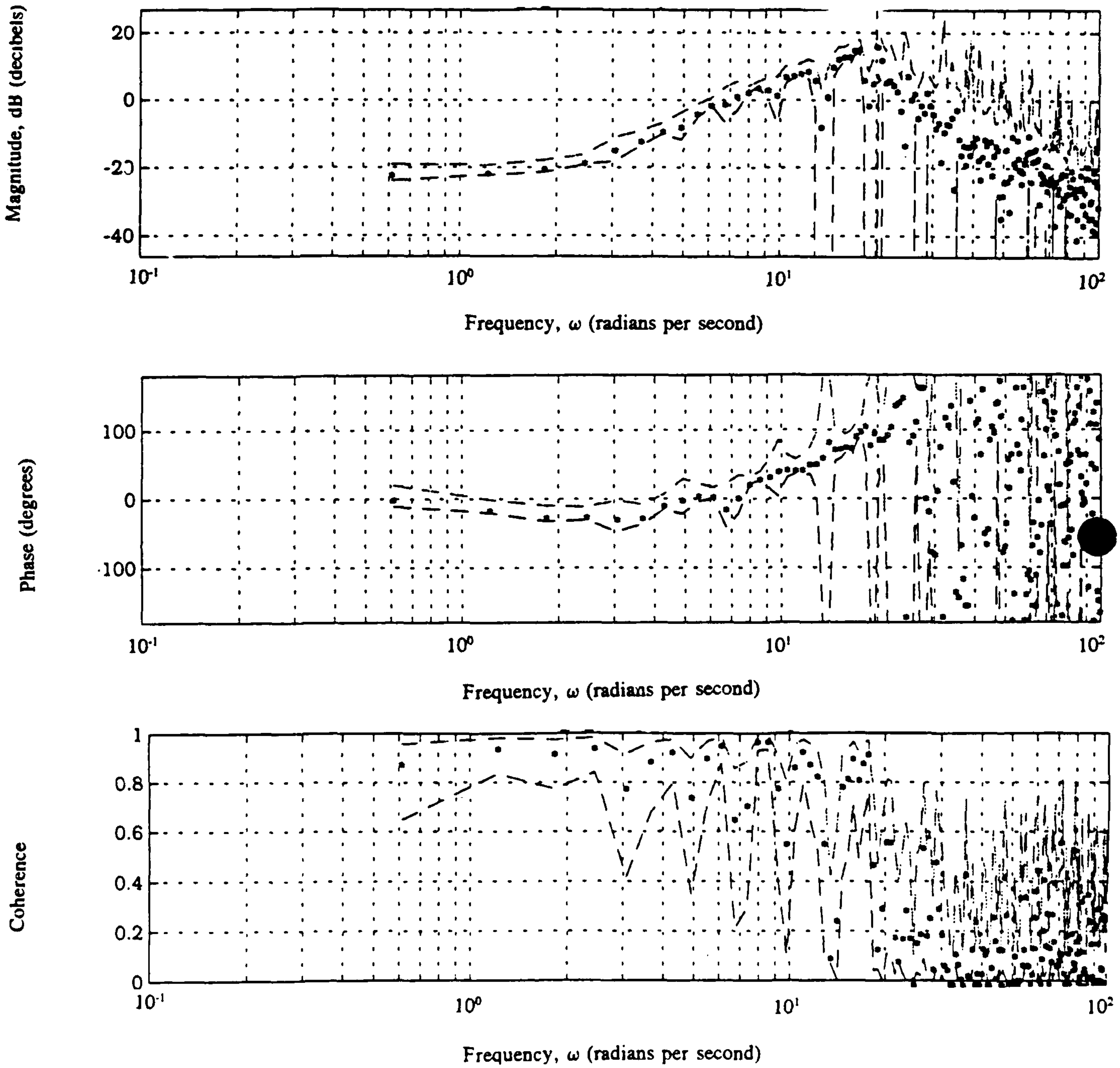

Figure N4: Frequency Response Analysis -
Lateral Stick Deflection to Task Error (File F4AS_G_4)

Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 10 Oct 93; Pilot: G; Sortie #3
Sum-of-Sines Tracking Task; Case 1D (See Appendix D)
Airborne Data

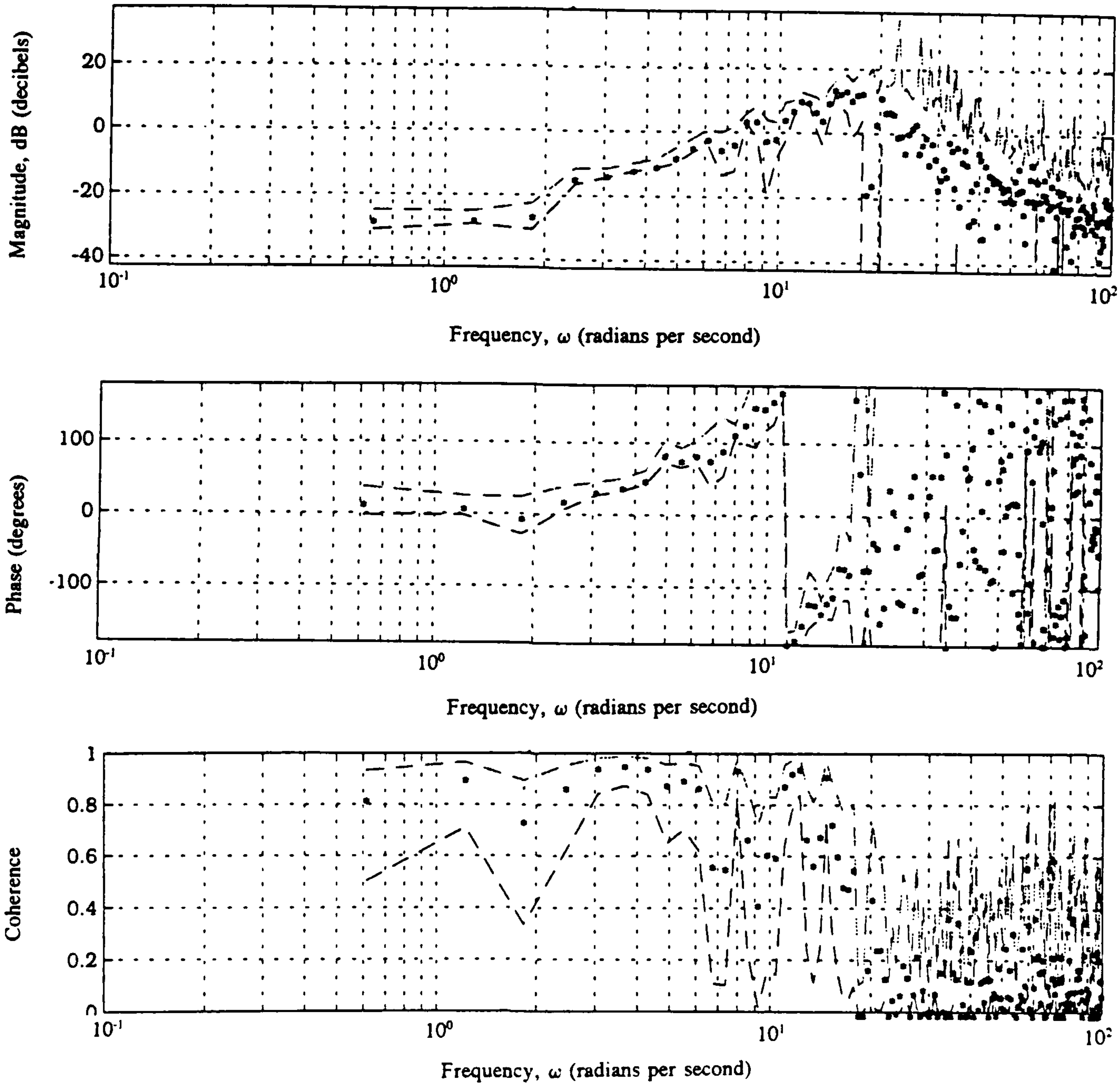

Figure N5: Frequency Response Analysis -
Longitudinal Stick Deflection to Task Error (File F1DS_G_3)

Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 10 Oct 93; Pilot: G; Sortie #3
Sum-of-Sines Tracking Task; Case 1D (See Appendix D)
Airborne Data

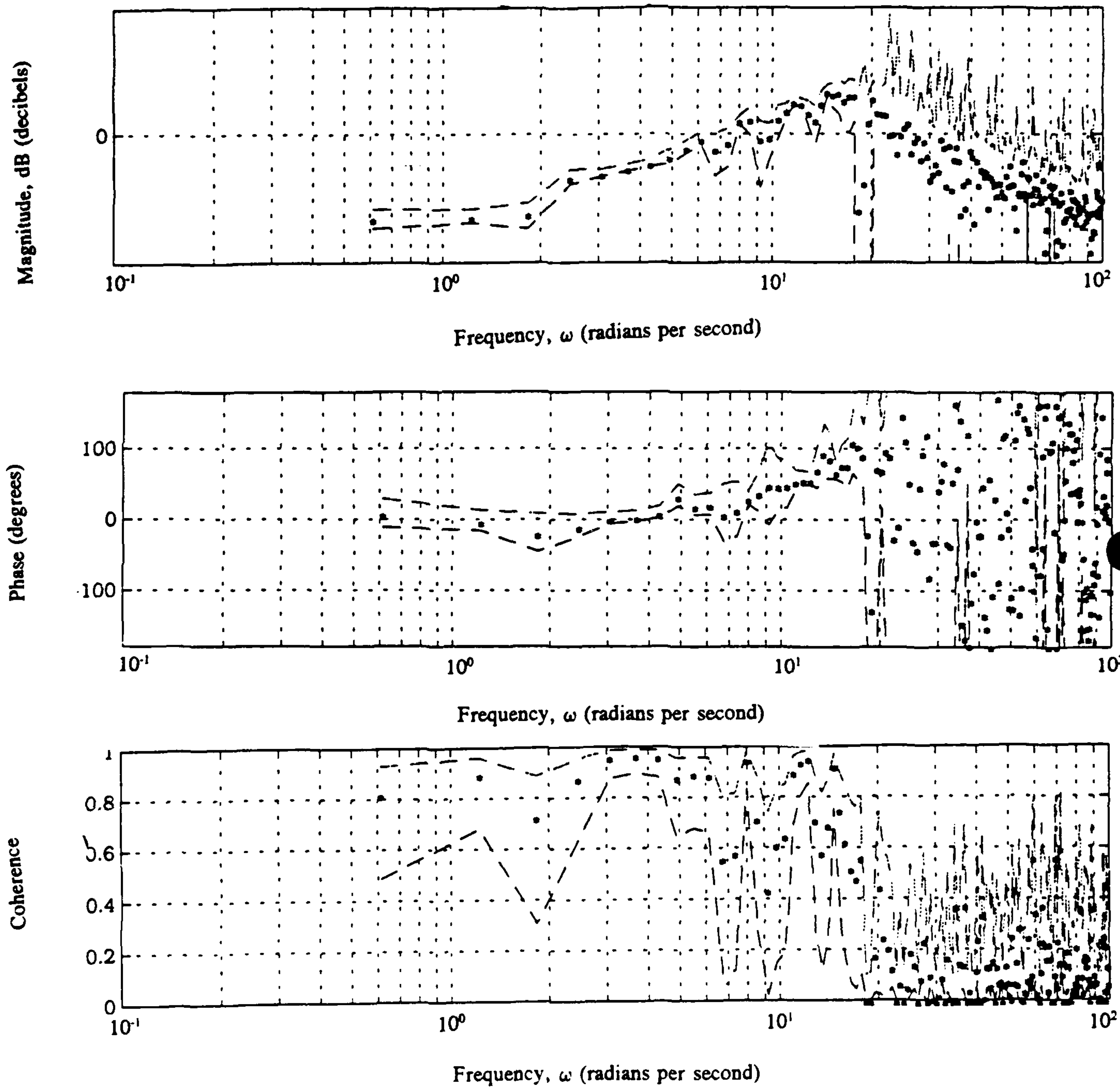

Figure N6: Frequency Response Analysis -
Lateral Stick Deflection to Task Error (File F1DS_G_3)

Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 11 Oct 93; Pilot: E; Sortie #5
Sum-of-Sines Tracking Task; Case 4D (See Appendix D)
Airborne Data

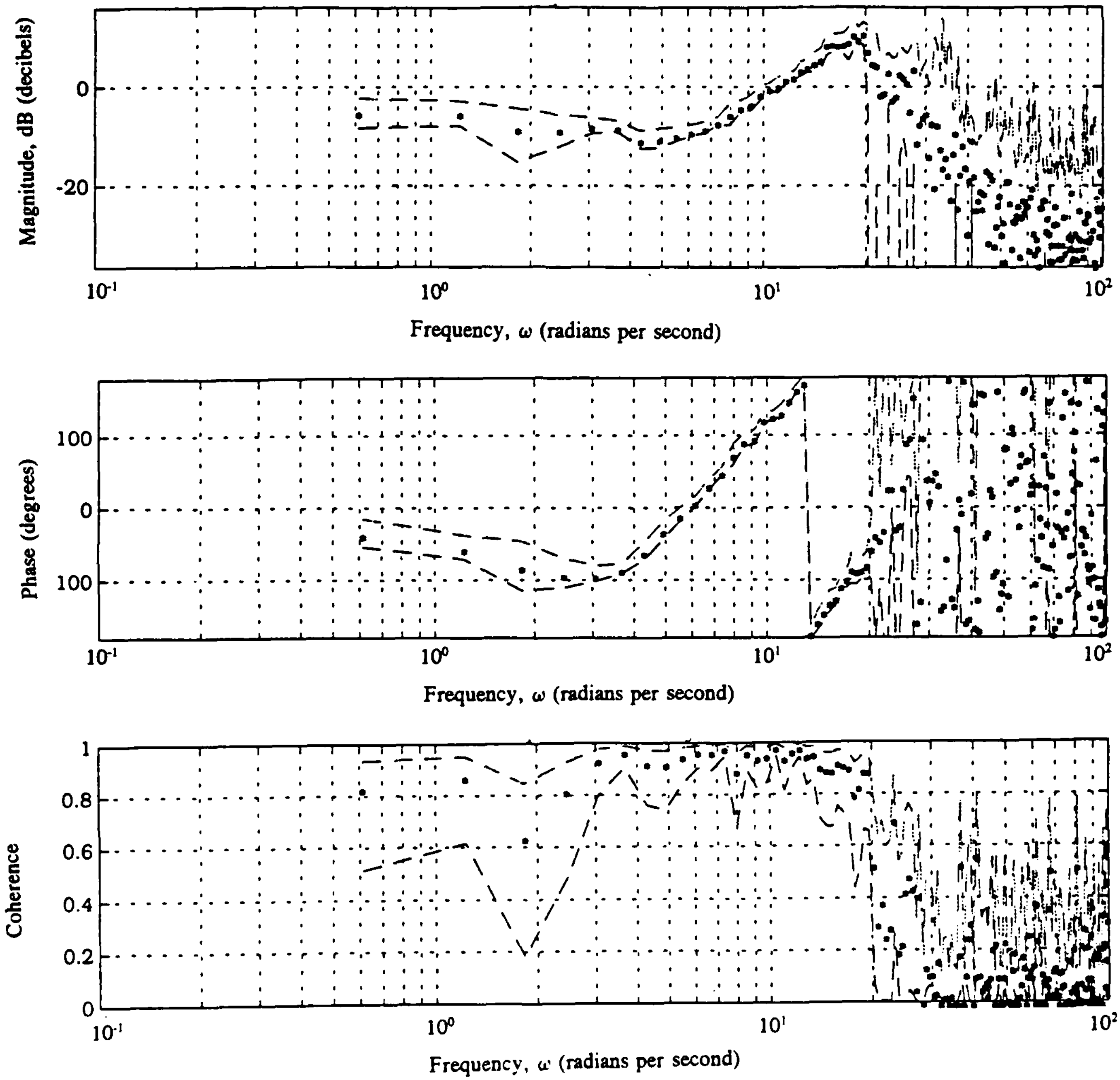

Figure N7: Frequency Response Analysis -
Longitudinal Stick Deflection to Task Error (File F4DS_E_5)

Calspan Variable Stability Aircraft
Learjet LJ-25, Tail Number N102VS
Date: 11 Oct 93; Pilot: E; Sortie #5
Sum-of-Sines Tracking Task; Case 4D (See Appendix D)
Airborne Data

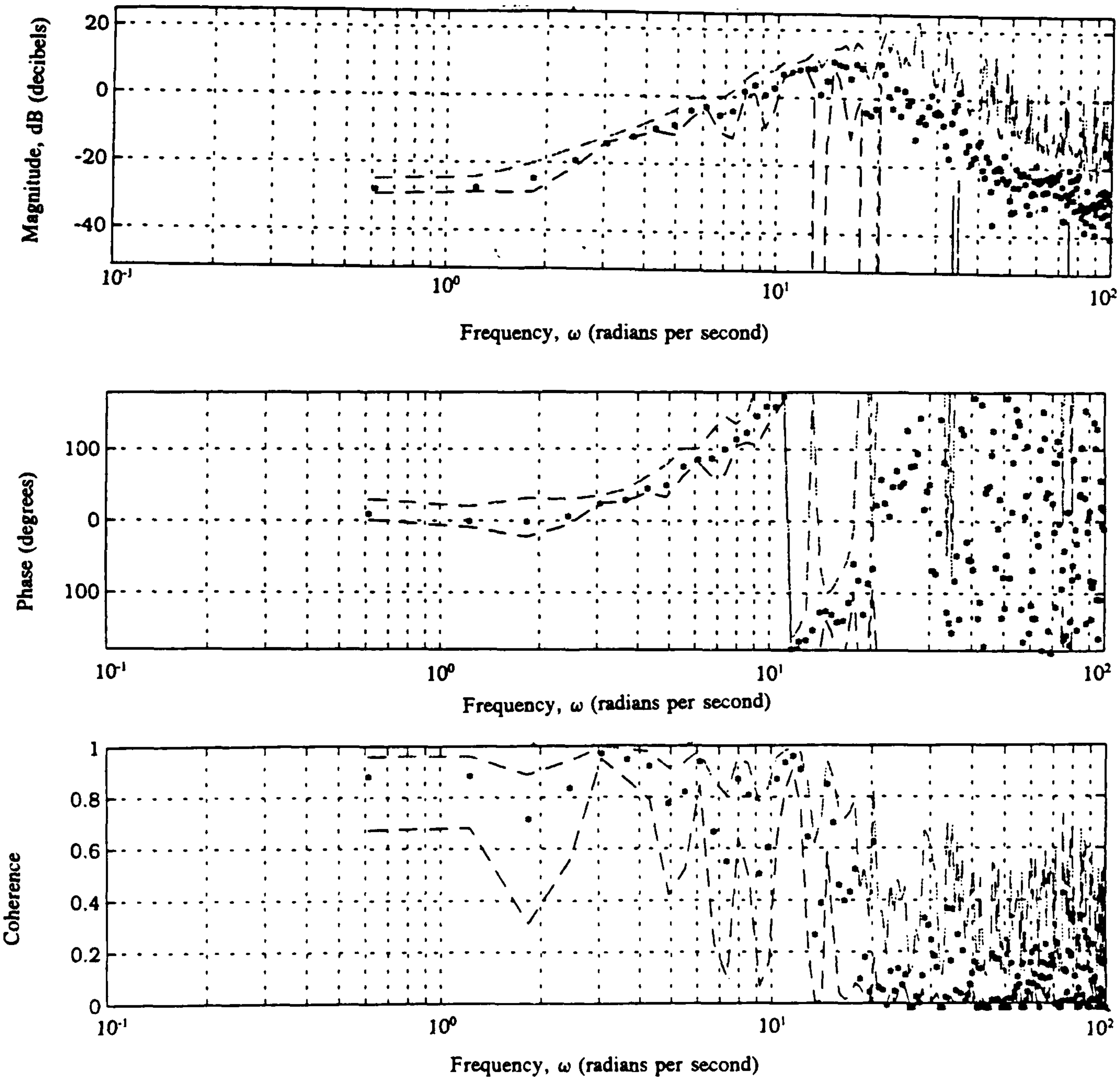

Figure N8: Frequency Response Analysis -
Lateral Stick Deflection to Task Error (File F4DS_E_5)

APPENDIX O

PILOT MODEL PREDICTIONS

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Pitch Axis Dynamics:

$$\frac{\theta}{\delta_{as}} = 8 \cdot \frac{4900}{s^2+98s+4900} \cdot \frac{5.5(s+1.8)}{s(s^2+12\zeta+36)} \cdot e^{-\tau_D s}$$

Table O1: MIL-STD-1797A Pilot Model Predictions (Pitch)

CASE	ζ τ_D	C-H[1] Rating	CAP[2]	SP[3]	TRP[4]	BW[5] Criteria	Neal Smith Criteria	Gibson's Criteria	OPM[6]
1	.7 .04	1-3	I	II	I	II	II	Abrupt Bobbling Tendency	3.4
2	.4 .04	1-2	I	I	I	I-II	II	Abrupt Bobbling Tendency	3.8
3	.7 .24	3-5	III	III	III	III	III	Satisfactory Response	4.3
4	.4 .24	4	III	III	III	III	III	Satisfactory Response	4.5

[1]Cooper-Harper Ratings from flight test data.
[2]Control Anticipation Parameter Criteria
[3]Short Period Criteria
[4]Transient Response Parameter
[5]Bandwidth Criteria
[6]Optimal Pilot Model Cooper-Harper Rating Prediction

Roll Axis Dynamics:

$$\frac{\phi}{\delta_{as}} = 12 \cdot \frac{4900}{(s^2+98s+4900)} \cdot \frac{3.3}{s(s+T_R)} \cdot e^{-\tau_D s}$$

Table O2: MIL-STD-1797A Pilot Model Predictions (Roll)

CASE	T_R τ_D	C-H Rating[1]	Bandwidth[2]	Roll Constant	Spiral Constant	Delay	Step Resp	OPM[3]
A	.4 .04	1-3	2	I	I	I	I	3.8
B	1 .04	2-4	3	I-II	I	I	I	5.3
C	.4 .24	4-5	4	I	I	III	I	5.2
D	1 .24	5-7	5	I-II	I	III	I	10

[1]Cooper Harper Ratings Range from flight test data.
[2]Bandwidth rating is from the regression formula in Reference 4.
[3]Optimal Pilot Model Cooper-Harper Rating Prediction

The dynamics simulated in this flight test were evaluated using the optimal pilot model developed by Systems Technology, Incorporated, in Reference 8. The parameters given in Table O1 were used when running this model.

Table O3
Optimal Pilot Model Parameters

Forcing Function, Y_w (at Plant Output)	$\frac{\sqrt{2}}{6.25s^2+3.54s+1}$	Motor Noise Ratio, ρ_m	-20 dB
Neuro-Muscular Time Constant, τ_N	0.08	Visual Indifference Thresholds, T_{y1} T_{y2}	0
Pilot Delay, τ_p	0.25 seconds	Fractional Attention Parameter, f	1
Observation Noise Ratios, ρ_{y1} ρ_{y2}	-20 dB	Driving Noise Intensity, V_w	1

This optimal pilot model used a Kalman filter, a predictor-corrector, and a linear quadratic regulator to model pilot behavior. It assumed that pilot opinion ratings are a function of performance (task error) and workload (stick rate). The model worked to find the pilot transfer function that minimized a performance index consisting of these two parameters. This performance index was then used to predict a Cooper-Harper rating based on the regression analysis with past data.

This optimal pilot model also returned a predicted pilot transfer function for each dynamics case. Bode plots of selected pilot transfer functions and the combined aircraft-pilot system are given in Figures O1 through O4. These plots were used for comparison with actual flight test data.

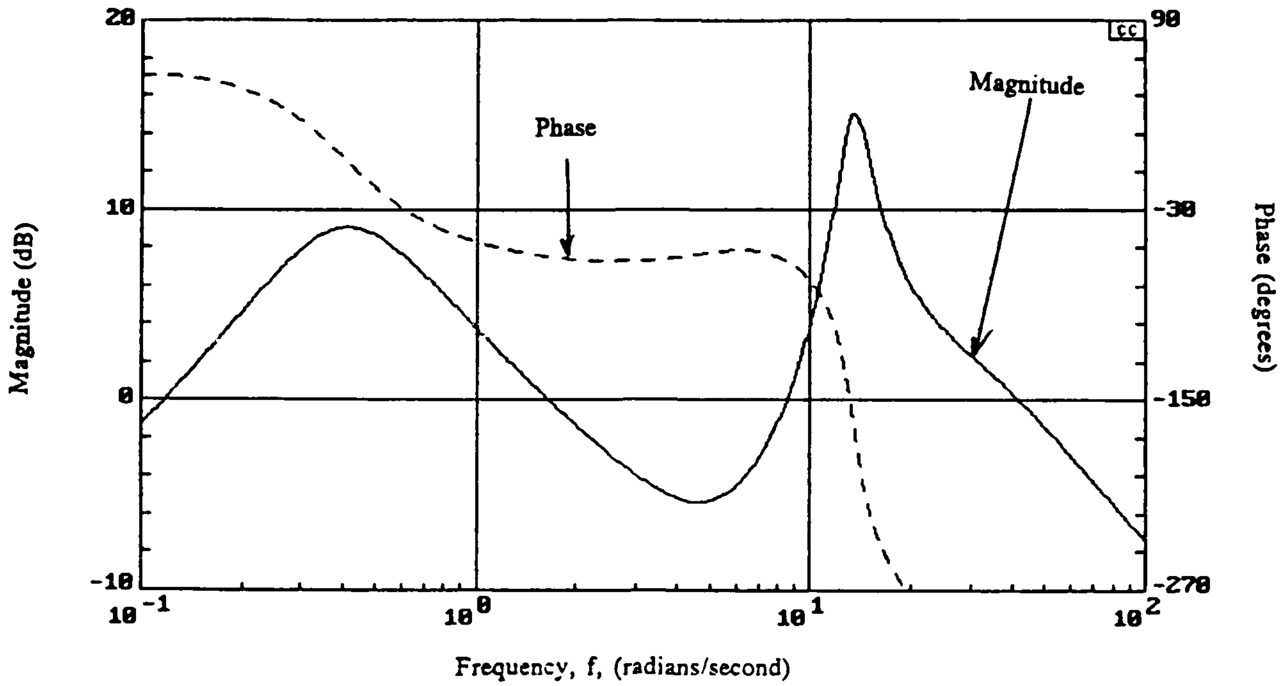

Figure O1: Bode Plot of Predicted Pilot Transfer Function (Case 1)

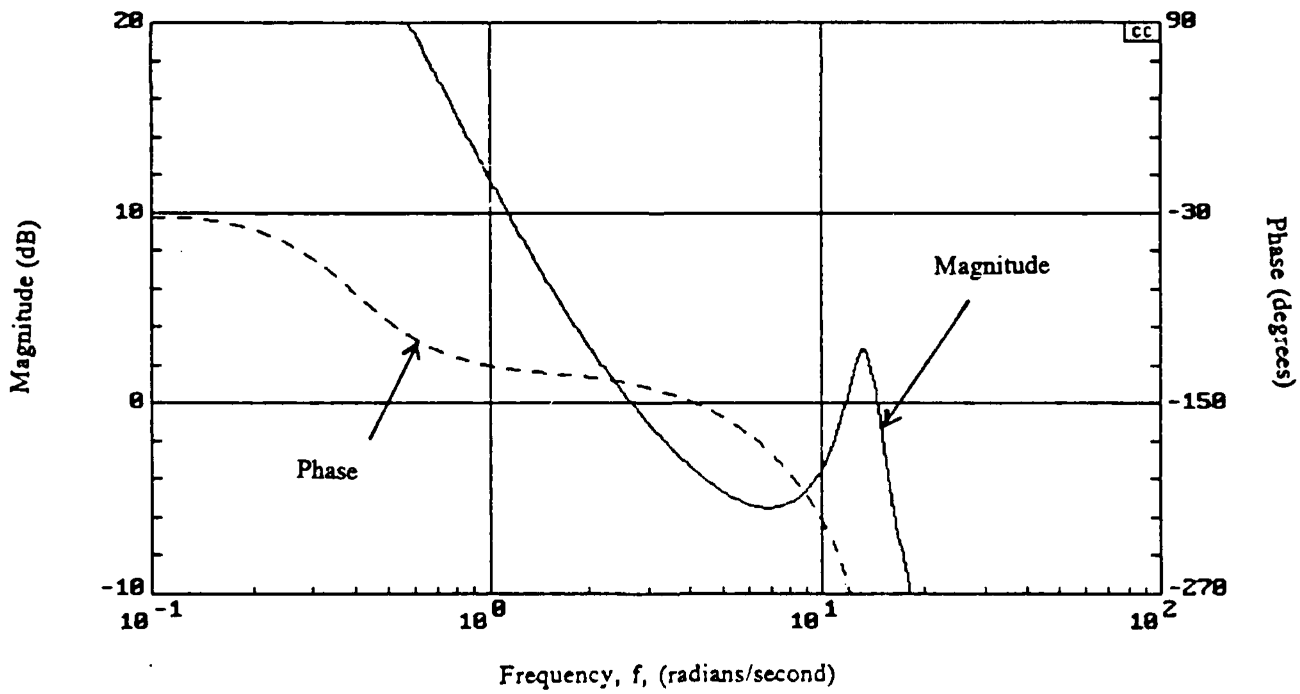

Figure O2: Bode Plot of Predicted Pilot-Aircraft System (Case 1)

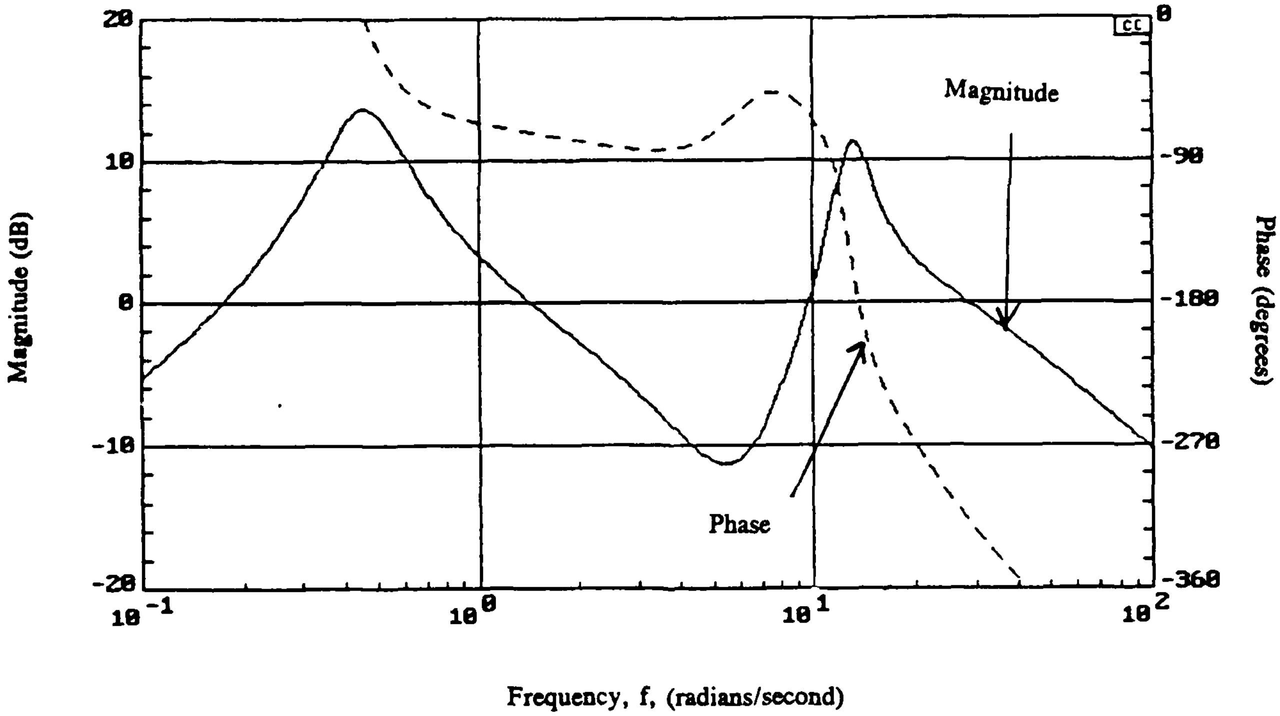

Figure O3: Bode Plot of Predicted Pilot Transfer Function (Case 4)

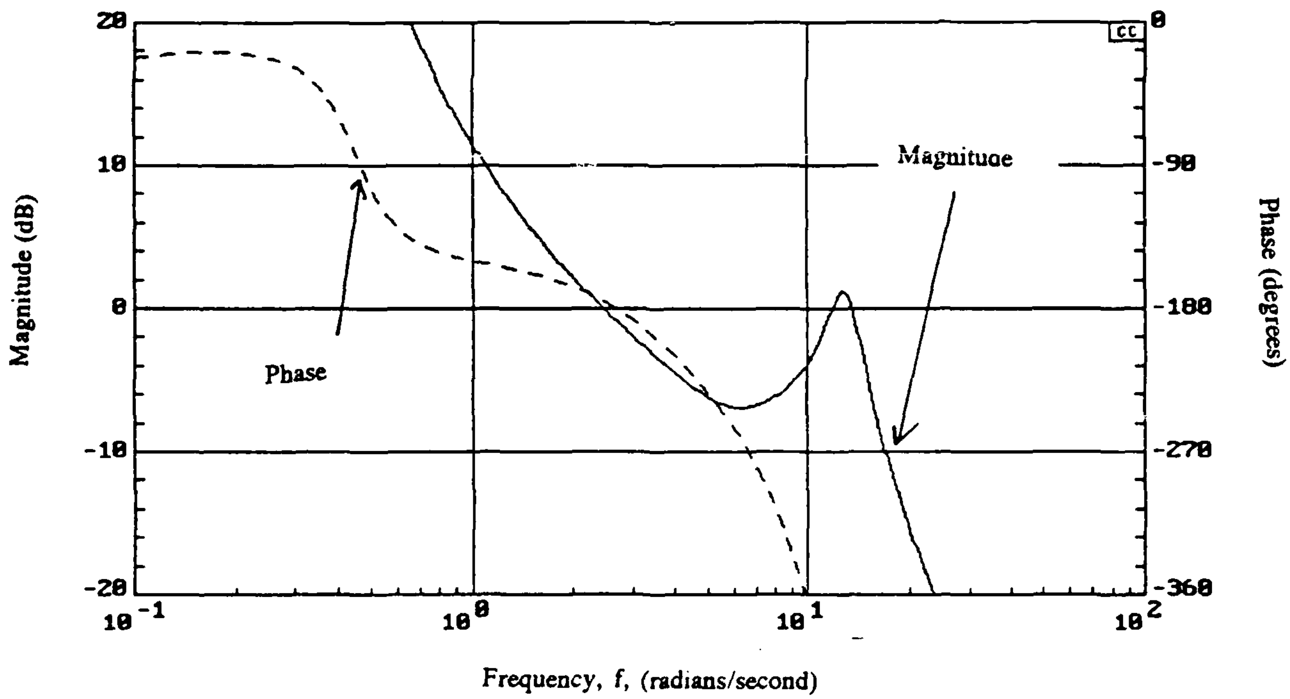

Figure O4: Bode Plot of Predicted Pilot-Aircraft System (Case 4)

LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS	DEFINITION
AFB	Air Force Base
AFFTC	Air Force Flight Test Center
AIAA	American Institute for Aeronautics and Astronautics
AIM-9	Air Intercept Missile (-9)
ASCII	American Standard Code for Information Interchange
CF	Canadian Forces
FRA	Frequency Response Analysis
g	Acceleration Due to Gravity
Hz	Hertz
ISA	Industry Standard Architecture
JON	Job Order Number
LAMARS	Large Amplitude Multi-Mode Aerospace Research Simulator
LCD	Liquid Crystal Display
LJ-25	Learjet 25
MHz	Megahertz
MS-DOS	Micro-Soft Disk Operating System
PA	Pressure Altitude
PC	Personal Computer
PIO	Pilot Induced Oscillation
PSD	Power Spectral Density
RAM	Random Access Memory
SOS	Sum-of-Sines
STI	Systems Technology, Incorporated
TLR	Technical Letter Report
USAF TPS	United States Air Force Test Pilot School
VMC	Visual Meteorological Conditions
WL/FIGC	Air Force Flight Dynamics Directorate
412 TW/TSWS	412 Test Wing, Technical Support Division
412 TW/DOEF	412 Test Wing, Engineering Division

LIST OF ABBREVIATIONS AND SYMBOLS (Continued)

SYMBOLS	DEFINITION	UNITS
Aerodynamic Parameters		
α	Angle of Attack	degrees
β	Side Slip	degrees
$\dot{\beta}$	Side Slip Rate	degrees per second
θ	Pitch	degrees
ϕ	Bank	degrees
p	Roll Rate	degrees per second
q	Pitch Rate	degrees per second
r	Yaw Rate	degrees per second
n_z, n_y	Normal Accelerations	g
n_{zp}, n_{yp}	Normal Accelerations at Pilot's Station	g
Control Parameters		
δ_e	Elevator Deflection	degrees
δ_a	Aileron Deflection	degrees
δ_r	Rudder Deflection	degrees
δ_{rp}	Rudder Pedal Deflection	degrees
δ_{es}	Longitudinal Stick Deflection	inches
$\dot{\delta}_{es}$	Longitudinal Stick Deflection Rate	inches per second
δ_{ec}	Commanded Elevator Deflection	degrees
δ_{as}	Lateral Stick Deflection	inches
$\dot{\delta}_{as}$	Lateral Stick Deflection Rate	inches per second
δ_{ac}	Commanded Aileron Deflection	degrees
F_{es}	Longitudinal Stick Force	pounds
F_{as}	Lateral Stick Force	pounds
F_s or F	Stick Force (general)	pounds
δ_s	Stick Deflection (general)	inches
Display Parameters		
θ_c	Pitch Command	degrees
ϕ_c	Roll Command	degrees
e_θ	Pitch Error	degrees
e_ϕ	Roll Error	degrees
$\dot{e}_\theta$	Pitch Error Rate	degrees per second
$\dot{e}_\phi$	Roll Error Rate	degrees per second
A_i	Amplitude for Sum-of-Sines Function	dimensionless
ω_i	Frequency for Sum-of-Sines Function	radians per second
ϕ_i	Phase for Sum-of-Sines Function	degrees

LIST OF ABBREVIATIONS AND SYMBOLS (Continued)

SYMBOLS	DEFINITION	UNITS
Dynamic Parameters		
ζ_{sp}	Short Period Damping Ratio	dimensionless
ω_{sp}	Short Period Natural Frequency	radians per second
τ_e	Equivalent System Delay	seconds
τ_R	Roll Mode Time Constant	dimensionless
s	Laplace Variable	dimensionless
Pilot Modeling Parameters		
$j\omega$	Laplace Variable for Random Input	dimensionless
Y_p	Pilot Output	dimensionless
K_p	Pilot Gain	dimensionless
τ	Pilot Delay	seconds
T_L	Pilot Lead Time Constant	dimensionless
T_I	Pilot Lag Time Constant	dimensionless
T_K	Very Low Frequency Pilot Lead Time Constant	dimensionless
T'_K	Very Low Frequency Pilot Lag Time Constant	dimensionless
T_N	Neuro-muscular Time Constant	dimensionless
ω_n	High Frequency Neuro-Muscular Natural Frequency	radians per second
ζ_n	High Frequency Neuro-Muscular Damping Ratio	dimensionless
Miscellaneous Parameters		
t	Time	seconds
#	Number	dimensionless

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